1-D Tolerance Chart Automate

An Undergraduate Honors Thesis
Submitted to the Department of Mechanical Engineering
The Ohio State University
In Partial Fulfillment of the Requirements
For Graduation with Distinction in Mechanical Engineering

Kreteeka Chaudhury
Spring 2018

ABSTRACT

In mass production, for ensuring interchangeability of parts and proper function, design engineer needs to specify the range of geometric and dimensional variations that is acceptable. This is done using Geometric Dimensioning and Tolerancing (GD&T) which has classified 14 different types of geometric characteristics needed for specification. When designers develop a GD&T scheme, they need to ensure that dependent dimensions such as clearances are within range to allow assembly and proper function. This requires analysis of the tolerance scheme. 3-D tolerance analysis is a non-linear problem that cannot be expressed in closed form so various simplified methods have been devised to do tolerance analysis. One of them is called 1-D minimum and maximum chart, which does tolerance analysis in one direction control at a time so it misses out in any couplings between the directions. However, it is still accurate for certain type of assemblies such as disk stack on a single shaft in a turbine. So, because of its simplicity it is a popular method used by many designers. However, the procedure is manual and requires mastering a large number of rules, each specific to a tolerance class to make the chart.

The purpose of this project is to automate the 1-D tolerance analysis process by making a 1-D Tolerance Stack Automate that will have all the tolerance analysis rules embedded in it and will perform the stack calculations automatically, freeing the user from learning the rules. The tool has been developed within MS Excel. Six files were made to incorporate all the rules based on tolerance class, based on the types of user inputs and similarity in rules required to perform the analysis. These six files are: (1) Size and basic dimension; (2) Runout and concentricity; (3) Profile; (4) Orientation and form (not FOS); (5) Orientation, straightness and cylindricity (FOS); (6) Position. Then each of these files were combined into one master MS Excel file. In total 11 test cases were performed on the individual files and the master file using different geometric parts

so that each condition is evaluated. The results from 1-D chart performed in Excel have been verified with those performed manually as both the approaches used standard GD&T rules.

ACKNOWLEDGEMENTS

I would like to begin by thanking my principal advisor, Dr. Jami J. Shah for giving me the opportunity to work on this project at Digital Design and Manufacturing Lab (DDML). His valuable insights and resources helped me complete the project.

I would also like to thank Payam Haghighi, Research Associate at DDML for helping me write my research proposal and helping me schedule meeting times with Dr. Shah and other lab members. His vast experience in conducting tolerance analysis helped me clear my initial doubts on the tolerance analysis rules.

I am thankful to Prof. Russell Marzette for taking the time to serve on my defense committee.

Thanks to Kaushalya Putta, Undergraduate Research Assistant at DDML. Her assistance helped me complete the first test of the master file, the surrogate gearbox.

The project would not have been complete without Kristen Hahyeon Kim, Undergrduate Research Assistant at DDML. Her fresh out of the box user reviews helped me realize the shortcomings of my initial user interface.

I would also like to thank Austin Scharff, Undergraduate Research Assistant at DDML. His exceptional mastery of tolerance rules helped me clear my concepts and deepened my understanding on minimum and maximum 1-D tolerance charts.

Finally, I would like to acknowledge my parents, Mr. Arun Kumar Chaudhury and Mrs. Kiran Devi Chaudhury for their constant support during stressful periods.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: Introduction

1.1 Geometric Dimensioning and Tolerancing (GD&T)

In most of the industries today, interaction between different parts is commonly observed. Hence, design engineers across different industries need to use GD&T to ensure interchangeability of parts across different companies and to preserve the intended function of the design. Hence, GD&T symbols were developed for engineering drawings to precisely communicate dimensional and geometric requirements.

GD&T comprises of 14 geometric characteristics symbols listed in Table 1. These symbols are classified into five different tolerance classes that form the backbone of tolerance analysis. Out of these 14 geometric characteristics, symmetry in the location tolerance class is a characteristic, which is not very commonly used and mostly dropped from GD&T standards. Hence, symmetry was not considered for this project.

Table 1: GD&T geometrical characteristics

Type of Tolerance	Symbol	Geometric Characteristics
Form	—	Straightness
	▱	Flatness
	○	Circularity
	⌭	Cylindricity
Profile	⌒	Profile of a line
	⌓	Profile of a surface
Orientation	∠	Angularity
	⊥	Perpendicularity
	//	Parallelism

Location	⌖	Position
	◎	Concentricity
	⌯	Symmetry
Runout	↗	Circular Runout
	⌰	Total Runout

Figure 1 below comprises of few GD&T symbols. It is a rectangular bar with a bolt-hole pattern. Table 2 illustrates the meaning of each of the symbols in Figure 1. The feature control frame on the center hole tells us that the diameter of the hole needs to be 22.2 with +/- 0.1 variations. Along with the size dimension, the engineer has specified another limit using the position tolerance symbol. It states that the center hole's axis position needs to be inside a cylinder of 0.2 diameter. This way of using GD&T, an engineer can specify acceptable limits to meet the design's functional requirements and reduce manufacturing cost by allowing variations.

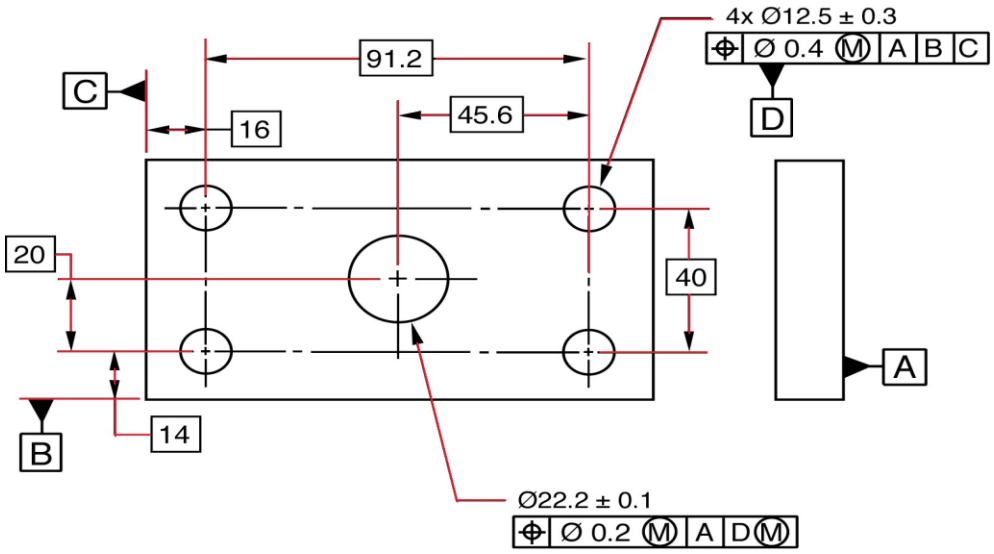


Figure 1: GD&T symbols on a bolt pattern drawing [1]

Table 2: Meaning of symbols in Figure 1

Symbols	Description
□	Basic Dimension
 [1]	Datum
⌖	Position Tolerance
Ⓜ	Maximum Material Condition

1.2 1D tolerance analysis

GD&T is also used to perform 1D tolerance analysis, which is done to "determine accumulation of all geometric variations of all contributing elements to a geometric attribute of interest" [2]. There are 23 rules (listed in Chapter 2.1), which needs to be accounted for to perform 1D tolerance analysis. Each rule is based on controls specific to a type of GD&T class (Table 1). There are two types of 1D tolerance analysis methods: (1) 1D statistical method; and (2) Worst case method. The critical difference between the two methods is that the worst case method also known as 1-D minimum and maximum tolerance chart method gives the user a definite maximum and minimum value between which the part dimension can vary whereas statistical method provides the normal distribution of the geometrical variation. 1D maximum and minimum chart is popular with small companies because of its simplicity and has been used for this project. 1D maximum and minimum chart can be performed for both parts and assemblies. Due to the time constraint, only 1D charts for parts have been considered for this project.

1.3 1-D minimum and maximum tolerance chart

This section will use a simple bolt and wall part (Figure 2) to explain the basics of 1D maximum and minimum chart method.

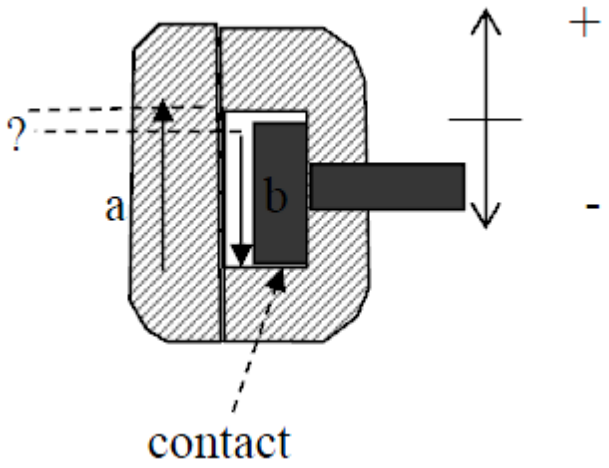


Figure 2: Bolt and wall part [2]

Tolerance analysis is done by first determining the stack path, which is the "shortest series of known dimensions from the origin to the other side of the unknown dimension," [2]. This is a radial stack and hence using the co-ordinate geometry system, the sign is +ve if travelling in upward direction and -ve if travelling in downward direction. For instance, the clearance required in Figure 2 can be determined by using the stack path: a-b. This seems very simple at the beginning and gives a wrong impression that maximum and minimum chart is just a process of addition and subtraction. It is true that 1-D chart requires only two mathematical operation: addition and subtraction but what governs the addition and subtraction is complex. For instance, the calculation in Figure 2 does not remain very simple when each part has different geometrical characteristics like perpendicularity and flatness associated with them as shown in Figure 3.

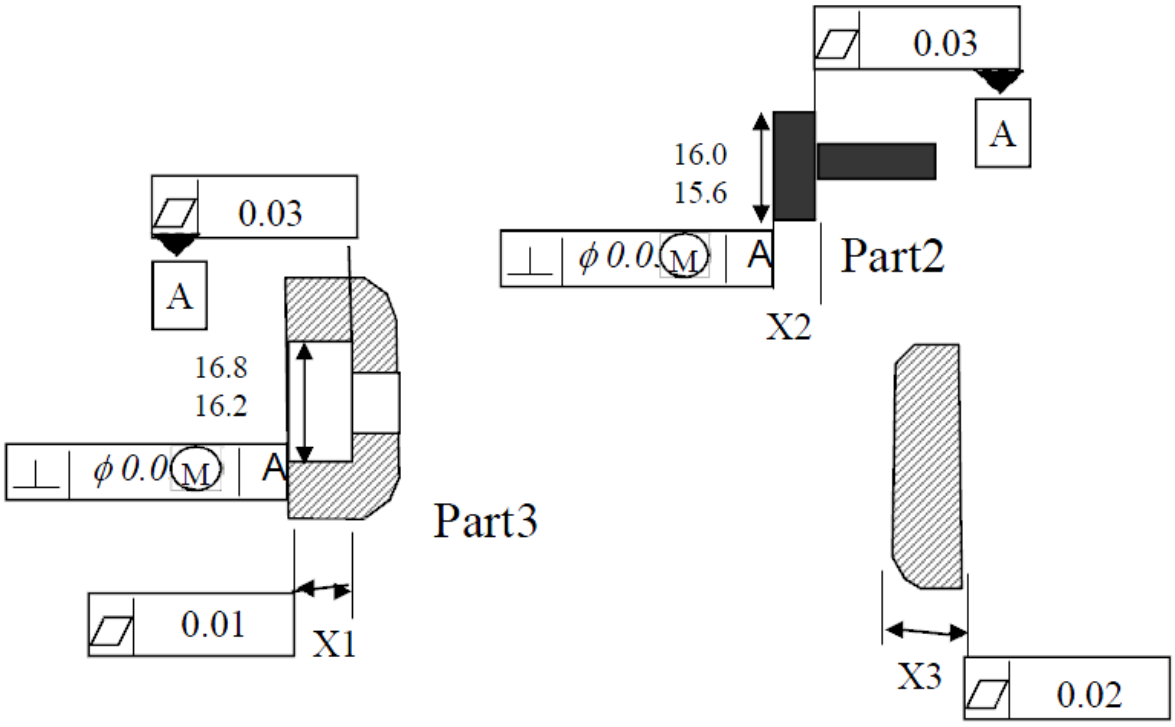


Figure 3: Geometrical characteristics on each part of the bolt and wall assembly [2]

Once the stack path is determined, a table similar to Table 3 is made. In the first and second column of Table 3, the part number and the stack contributor name is entered to identify the contributing part. In the third and the fifth column the sign (+/-) is entered based on the direction of travel or the rules. Then the maximum and minimum dimensions are entered in the fourth and sixth column based on the rules and the difference between the maximum and minimum dimension is entered in the last column. Once the table is completed, the values of maximum and minimum dimension are added and the average of the two sums gives the size dimension and the sum of the tolerance column gives the tolerance value of the interested geometry.

Table 3: 1-D Maximum and Minimum Chart Format

Part #	Stack Contributor	Sign	Maximum (Max/Min)	Sign	Minimum (Max/Min)	Δ

1.4 Thesis objectives

The purpose of my research is to automate 1-D tolerance chart generation. This will have all the 23 rules (listed in Chapter 2.1) embedded in it and will do the stack up calculations automatically assuming that the user is capable of finding the stack path and is aware of basic GD&T scheme. This will free the user from mastering the rules and avoid the hassle of flipping back and forth in the rules manual to complete the analysis.

1.5 Thesis overview

The thesis comprises of 10 chapters. Chapter 1 provided a brief background on GD&T, tolerance analysis and 1D maximum and minimum chart method. Chapter 2 discusses the methodology adopted to complete the project. Chapter 3 to Chapter 8 discusses the development of the six different individual files and the various test cases performed to evaluate them. Chapter 9 discusses the development of the master file and the test case performed for its evaluation. Finally, Chapter 10 summarizes the project and discusses additional application and future work.

CHAPTER 2: Methodology

2.1. Tolerance analysis rules comprehension

This section comprises of all the rules that have been automated to generate the 1D tolerance chart. The rules are listed based on the five tolerance classes mentioned in Table 1. These rules have been acquired from Dr. Jami J Shah's short course notes [5].

The first tolerance class is form which comprises of four different geometric characteristics as listed in Table 1. All the four geometric characteristics can be used on not Feature-of-size (FOS) parts and only straightness and cylindricity can be used on FOS parts. Hence, there are two different types of rules set for this tolerance class, one for FOS and one for not FOS. The rules for form tolerance class not FOS parts are as follows –

- If the stack goes thru the part, form and orientation tolerance on non-FOS are not included in the stack.
- If the part is adjacent to mating then first sign column is positive and second sign column is negative. The geometrical tolerance value is entered in maximum column and zero in minimum column.
- If the part is offset from mating then first sign column is positive and second sign column is negative. The geometrical tolerance value is entered in both maximum and minimum column.

In addition, the rules for straightness and cylindricity (FOS) are as follows –

- If direction of travel is +ve, enter +ve in both sign columns. If it is an internal FOS part, enter Least Material Condition (LMC) of size in maximum column and virtual condition (VC) of size in minimum column.

- If direction of travel is -ve, enter -ve in both sign columns. If it is an internal FOS part, enter virtual condition of size in maximum column and LMC of size in minimum column.
- If direction of travel is +ve, enter +ve in both sign columns. If it is an FOS external part, enter virtual condition of size in maximum column and LMC in minimum column.
- If direction of travel is -ve, enter -ve in both sign columns. If it is an external FOS part, enter LMC of size in maximum column and virtual condition of size in minimum column.

The second tolerance class listed in Table 1 is profile which comprises of two different geometric characteristics. When using the profile geometric characteristics in 1D chart, the following six rules needs to be accounted for –

- If there is no datum in the profile feature frame, then it is not used in the stack
- For equal bilateral profile tolerance, first sign column is positive and second sign column is negative and half of geometrical tolerance value is entered in both maximum and minimum columns.
- For unilateral profile tolerance, if direction of travel is +ve, both sign columns is +ve. The geometrical tolerance value is entered in maximum column and zero in minimum column.
- For unilateral profile tolerance, if direction of travel is -ve, both sign columns is -ve. The geometrical tolerance value is entered in minimum column and zero in maximum column.
- For unequal bilateral, if direction of travel is +ve, both sign columns is +ve. The greater specified portion is entered in maximum column and the other portion in the minimum

column.

- For unequal bilateral, if direction of travel is -ve, both sign columns is -ve. The greater specified portion is entered in minimum column and the other portion in the maximum column.

The third tolerance class is orientation which comprises of three different geometric characteristics as listed in Table 1. All the three geometric characteristics can be used on both FOS and not FOS parts. And like form, there are two different types of rules set for orientation tolerance class as well, one for FOS and one for not FOS. The rules for orientation tolerance class not FOS parts are as follows –

- If the stack goes thru the part then form and orientation tolerance on non FOS are not included in the stack.
- If the part is adjacent to mating then first sign column is positive and second sign column is negative. The geometrical tolerance value is entered in maximum column and zero in minimum column.
- If the If the part is offset from mating then first sign column is positive and second sign column is negative. The geometrical tolerance value is entered in both maximum and minimum column.

In addition, the rules for orientation (FOS) are as follows –

- If direction of travel is +ve, enter +ve in both sign columns. If it is an internal FOS part, enter LMC of size in maximum column and VC of size in minimum column.
- If direction of travel is -ve, enter -ve in both sign columns. If it is an internal FOS part, enter VC of size in maximum column and LMC of size in minimum column.

- If direction of travel is +ve, enter +ve in both sign columns. If it is an external FOS part, enter VC of size in maximum column and LMC in minimum column.
- If direction of travel is -ve, enter -ve in both sign columns. If it is an external FOS part, enter LMC of size in maximum column and VC of size in minimum column.

The fourth tolerance class is location, which comprises of three geometric characteristics namely: position, symmetry and concentricity. The rules for symmetry will not be discussed as symmetry is not been considered for this project due to reasons mentioned in Chapter 1. Each geometric characteristics in this tolerance class has its own set of rules. When using the position geometric characteristics in 1D chart, the following six rules needs to be accounted for –

- For each row, regardless of user inputs, first sign column is positive and second sign column is negative always.
- Half the geometrical tolerance value is entered in both maximum and minimum columns
- If it is a press fit then maximum radial bonus is entered in both maximum and minimum columns.
- If it is not a press fit and LMC or MMC modifier is used as a tolerance modifier, then zero bonus is entered in the column containing the MMC radius and maximum radial bonus is entered in the column containing the LMC radius.
- If it is a press fit and there is a MMC or LMC modifier used as a datum modifier, then maximum shift is entered in both maximum and minimum columns.
- If it is not a press fit and there is a MMC or LMC modifier used as a datum modifier, then minimum shift is entered in the column containing the MMC radius of the datum and maximum shift is entered in the column containing the LMC radius of the datum.

In addition, when using the concentricity geometric characteristics in 1D chart, the following rule should be used –

- First sign column is positive, and second sign column is negative always. Half of the geometrical tolerance value is entered in both the maximum and minimum column.

The last tolerance class is runout and it comprises of two geometric characteristics. When using runout characteristics in 1D chart following rule should be applied –

- First sign column is positive and second sign column is negative always. Half of the geometrical tolerance value is entered in both the maximum and minimum column.

In addition, to these five tolerance classes, GD&T comprises of size and basic dimensions. There are two rules that govern size dimension –

- If direction of travel is +ve, then +ve signs are entered in both the sign columns; maximum size is entered in the maximum column and minimum size in the minimum column.
- If direction of travel is -ve, then -ve signs are entered in both the sign columns; minimum size is entered in the maximum column and maximum size in the minimum column.

And the following one rule governs basic dimension –

- The signs are entered based on the direction of travel and same dimension is entered in both minimum and maximum column.

2.2 Determination of user inputs

Once the rules for each tolerance class, geometric characteristics and dimensions were comprehended, the number of user inputs required were determined to understand which categories can be combined into one single file. The user inputs listed below are based on the

rules and with the assumption that the tool will not have access to the drawing and so will require the user to input sufficient information to generate the 1D chart. However, attempt has been made to keep the number of user inputs to as low as possible so that the user does not have to input all the information from the drawing. The user inputs required for each tolerance classes with reasoning are as follows -

Form (not FOS): 3 user inputs

1. To or thru Stack: Required to determine if the part should be used in the stack or not
2. Mating condition: Required to determine which set of rule to apply
3. Geometrical tolerance value: Required to calculate maximum tolerance value.

Straightness and cylindricity (FOS): 5 user inputs

1. Direction of travel: Required to determine feature sign
2. Internal or external part: Required to know which formula to use while calculating MMC and VC
3. Nominal dimension: Required to calculate VC, LMC and MMC
4. Tolerance value: Required to calculate VC
5. Geometrical tolerance value: Required to calculate LMC and MMC

Profile: 6 user inputs

1. Any datum? Required to determine if the part should be included in the stack
2. Direction of travel: Required to determine sign of unequal bilateral or unilateral features
3. Nominal dimension: Required to determine feature type
4. + Tolerance value: Required to determine feature type
5. – Tolerance value: Required to determine feature type

6. Geometrical tolerance value: Required to calculate maximum and minimum tolerance values

Orientation (not FOS): 3 user inputs

1. To or thru Stack: Required to determine if the part should be used in the stack or not
2. Mating condition: Required to determine which set of rule to apply
3. Geometrical tolerance value: Required to calculate maximum tolerance value.

Orientation (FOS): 5 user inputs

1. Direction of travel: Required to determine feature sign
2. Internal or external part: Required to know which formula to use while calculating MMC and VC
3. Nominal dimension: Required to calculate VC, LMC and MMC
4. Tolerance value: Required to calculate VC
5. Geometrical tolerance value: Required to calculate LMC and MMC

Position: 11 user inputs

1. Press fit: Required to determine if centerline of FOS condition should be applied to calculate bonus and shift
2. Internal or external part: Required to know which formulae to use for MMC, LMC and VC
3. Direction of travel: Required to know which column consists LMC radius and MMC radius
4. Nominal dimension: Required to calculate MMC, LMC and VC
5. Tolerance value: Required to calculate MMC, LMC and VC
6. Geometrical tolerance value: Required to calculate bonus and position tolerance values

7. Tolerance modifier: Required to determine which set of formulae to use.
8. Datum modifier details
    a. Datum modifier: Required to determine if there is shift tolerance in the part
    b. Nominal Dimension: Required to calculate MMC, LMC and VC of the shift tolerance
    c. Tolerance Value: Required to calculate MMC, LMC and VC of the shift tolerance
    d. Geometrical Tolerance Value: Required to calculate MMC, LMC and VC of the shift tolerance

Concentricity: 1 user input

1. Geometrical tolerance value: Required to calculate maximum and minimum tolerance value

Runout: 1 user input

1. Geometrical tolerance value: Required to calculate maximum and minimum tolerance value

Size dimension: 3 user inputs

1. Direction of travel: Required to determine feature sign
2. Nominal dimension: Required to calculate maximum and minimum variation
3. Tolerance value: Required to calculate maximum and minimum variation

Basic dimension: 2 user inputs

1. Direction of travel: Required to determine sign feature
2. Nominal dimension: Required to determine maximum or minimum dimension value

2.3 Categorization

In this section, each of the tolerance class rules and user inputs were studied to determine the number of individual files required to complete 1-D Tolerance Chart Automate. The purpose of this stage was to determine if it is possible to combine any two different tolerance classes to minimize the number of individual files user has to switch in between to perform the analysis.

As it can be seen from section 2.1 and 2.2 form (not FOS) and orientation (not FOS) follows the same rules and consists of the same number and type of user inputs, so these two categories can be combined into one category: Orientation and form (not FOS). Also, straightness and cylindricty (FOS) and orientation (FOS) comprises of the same number of user inputs and follows the same rules, so they can be combined into one category: Orientation, straightness and cylindricity (FOS). In addition, runout and concentricity also follow the same rule, has same type of user input, and hence can be combined into one file: Runout and concentricity. Two other categories, size dimension and basic dimension although does not follow the same rules nor has the same number of user input, can be combined into one file: Size and basic dimension. This combination is possible because like size dimension, basic dimension sign columns follow the sign of direction of travel and the maximum and minimum column values are decided based on the direction of travel. The only difference between the two is that the tolerance value of basic dimension is zero. So, if the user does not enter tolerance value in case of basic dimension or enters zero then the same logic can be used for both dimensions.

Therefore, by comprehending the rules and determining the different types of user inputs for each category, the number of categories reduced from 10 to 6 following categories –

1. Size and basic dimension
2. Runout and concentricity: consists of 3 GD&T geometric characteristics
3. Profile: consists of 2 GD&T geometric characteristics

4. Orientation and form (not FOS): consists of 7 GD&T geometric characteristics
5. Orientation, straightness and cylindricity (FOS): consists of 5 GD&T geometric characteristics
6. Position: consists of 1 GD&T geometric characteristic

2.4 Selection of existing programming platforms

At the beginning of the project, three software: C++, MATLAB and MS excel were considered to automate the 1D chart process due to my acquaintance with these programming platforms. After making the different categories and determining the different user inputs required to perform the chart automatically, it was well known that the tool requires two critical component: user input capability and tabling format. While all the three platforms are capable of doing both, MS Excel stood out amongst the three due to its ease of usage as the project is constrained within two semesters. MS Excel also has numerous in built mathematical operations in form of a spreadsheet and consists of drop down menu formats. Due to theses advantages, it was determined to develop the tool within MS Excel.

2.5 Development of files

Once the various geometric characteristics were grouped in six different categories, an individual file for each category was made by following these four steps –

1. Pseudocode: This involved writing the rule in an “If and Else” format to generate a simplified logic from the rule.
2. MS Excel file: This involved transferring the pseudocode into MS Excel syntax and creating the individual files.
3. Pseudo test case: This involved testing the file with a pseudo case for a quick verification that the file is outputting the intended results.

4. Test: Finally, actual part cases were tested on the tool whose results were already available in the lab to verify the files created.

After each individual file was created, several considerations were made to combine the files into one master file so that the user has to deal with only one file instead of six different files. The following steps were taken to create the master file –

1. File combination: This involved combining different individual files into one single master file.
2. User test: In this step, a newly hired lab member was asked to use 1-D Tolerance Chart Automate to get feedback on the user interface of the tool.
3. Changes after user test: After the user test, the user feedbacks were incorporated.
4. Test: Here, a surrogate gearbox tolerance analysis was conducted whose manual tolerance analysis has already been conducted by DDML lab members to verify the master file.

CHAPTER 3: Development of Size and Basic Dimension Individual File

3.1 Development of pseudocode

The size and basic dimension rules are simple and easy to understand. There are two rules that govern size dimension and one rule that governs basic dimension. For size dimension:

Rule #1: If direction of travel is +ve, then +ve signs are entered in both the sign columns; maximum size is entered in the maximum column and minimum size in the minimum column.

Rule #2: If direction of travel is -ve, then -ve signs are entered in both the sign columns; minimum size is entered in the maximum column and maximum size in the minimum column.

For basic dimension:

Rule #3: The signs are entered based on the direction of travel and same dimension is entered in both minimum and maximum column.

According to the rule, following four user inputs were deemed necessary to perform 1-D chart automatically:

- Tolerance Type (TT): A drop down menu with two options: size dimension and basic dimension
- Direction of Travel (DT): A drop down menu with two options: + and -
- Nominal Dimension (ND): User enters the nominal dimension here from the part drawing
- Tolerance Value (TV): User enters the tolerance value here from the part drawing

Once the rules and user inputs were comprehended, a pseudocode was written to detail the logic from the rules in programming language of "If and Else". The pseudocodes were written based on the user inputs for each of the four columns in 1D chart:

Left sign column (LSC)

If (DT = Blank)

Then (LSC = “ ”)

Else If (DT = “+”)

Then (LSC = “+”)

Else (LSC = “-”)

Maximum column (MAXC)

If (DT = Blank)

Then (MAXC = “ ”)

Else If (TT = “Size Dimension” & DT = “+”)

Then (MAXC = +(ND+TV))

Else If (TT = “Size Dimension” & DT = “-”)

Then (MAXC = -(ND-TV))

Else If (TT = “Basic Dimension” & DT = “+”)

Then (MAXC = ND)

Else If (TT = “Basic Dimension” & DT = “-”)

Then (MAXC = -ND)

Right sign column (RSC)

If (DT = Blank)

Then (RSC = “ ”)

Else If (DT = “+”)

Then (RSC = “+”)

Else (RSC = “-”)

Minimum column (MINC)

If (DT = Blank)

Then (MINC = “ ”)

Else If (TT = “Size Dimension” & DT = “+”)

Then (MINC = (ND-TV))

Else If (TT = “Size Dimension” & DT = “-”)

Then (MINC = -(ND+TV))

Else If (TT = “Basic Dimension” & DT = “+”)

Then (MINC = ND)

Else If (TT = “Basic Dimension” & DT = “-”)

Then (MINC = -ND)

3.2 Development of MS Excel file

The pseudocode was then transferred to MS Excel syntax and the file (Figure 4) was completed. As it can be seen in Figure 4, the user enters the information in the table on the left and the automated chart is generated on the right of the sheet. The cell numbers in MS Excel for the different user inputs are as follows –

- Tolerance Type : D4
- Direction of Travel : E4
- Nominal Dimension : F4
- Tolerance Value : G4

The lines of code written in MS Excel for each of the four column are as follows –

- Left sign column: “=IF(E4="+","+",IF(ISBLANK(E4)," ","-"))”

- Maximum column: “=IF(ISBLANK(E4)," ",IF(D4="Size Dimension", IF(E4="+",+(F4+G4),-(F4-G4)),IF(E4="+",F4,-F4)))”
- Right sign column: “=IF(E4="+","+",IF(ISBLANK(E4)," ","-"))”
- Minimum column: “=IF(ISBLANK(E4)," ",IF(D4="Size Dimension",IF(E4="+",(F4-G4),-(F4+G4)),IF(E4="+",F4,-F4)))”

Insert the information here					
Part #	Stack Contributor	Tolerance Type	Direction of Travel	Nominal Dimension	Tolerance Value

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
	Total		0		0	0
Final Result				0	±	0

Figure 4: Size and basic dimension automated tolerance chart file

3.3 Pseudo test case and results

For a quick verification, the following pseudo test case was performed. If the user entered the information in Table 4 then the 1D tolerance chart as seen in Table 5 was expected.

Table 4: Size and basic dimension pseudo test user inputs

User Inputs				
Sl. No.	Tolerance Type	Direction of Travel	Nominal Dimension	Tolerance Value
1	Size Dimension	+	5	3

2	Size Dimension	-	5	3
3	Basic Dimension	+	5	0
4	Basic Dimension	-	5	0

Table 5: Size and basic dimension pseudo test expected 1-D tolerance chart

Expected 1-D Tolerance Chart					
Sl. No.	**Sign**	**Maximum**	**Sign**	**Minimum**	**Δ**
1	+	+8	+	+2	6
2	-	-2	-	-8	6
3	+	+5	+	+5	0
4	-	-5	-	-5	0
	Total	6		-6	12

Then same user input as listed in Table 4 was inserted in the size and basic dimension file as seen in Figure 5 and the automated tolerance chart was generated as evident from Figure 6.

Insert the information here					
Part #	**Stack Contributor**	**Tolerance Type**	**Direction of Travel**	**Nominal Dimension**	**Tolerance Value**
	a	Size Dimension	+	5	3
	b	Size Dimension	-	5	3
	c	Basic Dimension	+	5	
	d	Basic Dimension	-	5	

Figure 5: Screenshot of the size and basic dimension pseudo test user inputs

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
	a	+	8	+	2	6
	b	-	-2	-	-8	6
	c	+	5	+	5	0
	d	-	-5	-	-5	0
Total			6		-6	12
Final Result				0	±	6

Figure 6: Screenshot of size and basic dimension pseudo test automated 1-D tolerance chart

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the expected 1-D chart results. Hence, verifying the logic of the program.

3.4 Test case and results

After the pseudo test case was successfully executed, an actual test case (Figure 7) was analyzed to verify the file developed. The geometric area of interest of this part is dimension "A" and can be found by using the stack path: - a – b + c – d - e

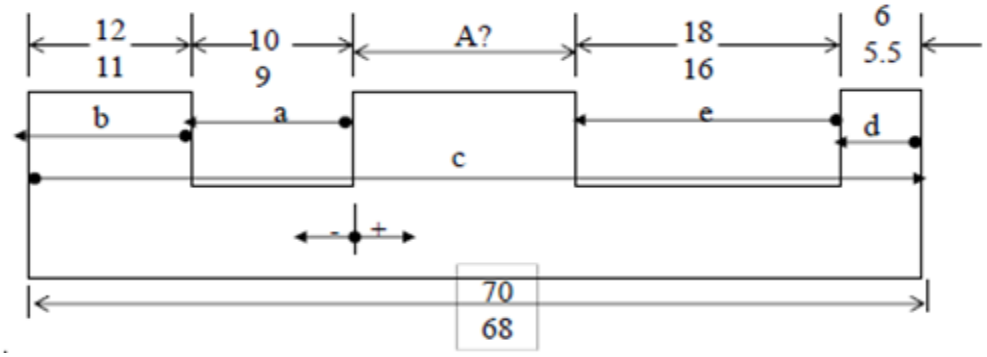


Figure 7: Size and basic dimension test case [2]

Based on the stack path, the information was entered as shown in Figure 8 and the automated chart was generated as shown in Figure 9.

Insert the information here					
Part #	Stack Contributor	Tolerance Type	Direction of Travel	Nominal Dimension	Tolerance Value
	a	Size Dimension	-	9.5	0.5
	b	Size Dimension	-	11.5	0.5
	c	Size Dimension	+	69	1
	d	Size Dimension	-	5.75	0.25
	e	Size Dimension	-	17	1

Figure 8: Screenshot of size and basic dimension test case user inputs

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
	a	-	-9	-	-10	1
	b	-	-11	-	-12	1
	c	+	70	+	68	2
	d	-	-5.5	-	-6	0.5
	e	-	-16	-	-18	2
Total			28.5		22	6.5
Final Result				25.25	±	3.25

Figure 9: Screenshot of size and basic dimension test case automated tolerance chart

While performing the 1-D tolerance chart manually, exact results were obtained. Thus, verifying the size and basic dimension file.

3.5 File limitations

The size and basic dimension file has only one limitation, which is that it works only for bilateral tolerance types and not for unilateral or unequal tolerance types. Bilateral tolerance type was used here, as they are comparatively more common in the industry. However, a simple change in logic will allow incorporating other tolerance types, something which can be taken care of in near future work.

CHAPTER 4: Development of Runout and Concentricity Individual File

4.1 Development of pseudocode

Both types of runout (circular runout and total runout) and concentricity follow the same rule:

Rule #4: First sign column is positive and second sign column is negative always. Half of the geometrical tolerance value is entered in both the maximum and minimum column.

Since, the rule only depends on the geometrical tolerance value, so only following one user input was required:

- Geometrical Tolerance Value (GTV): Here, the user enters the geometric tolerance value from the drawing

Once the rules and user inputs were comprehended, a pseudocode was written to detail the logic from the rules in programming language of "If and Else". The pseudocodes were written based on the user inputs for each of the four columns in 1D chart:

Left sign column (LSC)

If (TV = Blank)

Then (LSC = " ")

Else If (LSC = "+")

Maximum column (MAXC)

If (TV=Blank)

Then (MAXC = " ")

Else (MAXC = +GTV/2)

Right sign column (RSC)

If (TV = Blank)

Then (RSC = “ ”)

Else If (RSC = “-”)

Minimum column (MINC)

If (TV=Blank)

Then (MINC = “ ”)

Else (MINC = -GTV/2)

4.2 Development of MS Excel file

The pseudocode was then transferred to MS Excel syntax and the file (Figure # 10) was completed. To keep consistency with the size and basic dimension file, the user needs to input the information on the left table and the automated chart is generated on the right hand table. The cell numbers in MS Excel for the different user inputs are as follows –

- Tolerance Type: D4

  Tolerance type is not a required user input but will help the user keep track of the type of tolerance entered to be ensure consistency when performing the automated chart
- Geometric Tolerance Value : E4

The lines of code written in MS Excel for each of the four column are as follows –

- Left sign column: “=IF(ISBLANK(D4)," ","+")”
- Maximum column: “=IF(ISBLANK(E4)," ",IF(I4="+",+E4/2,-E4/2))”
- Right sign column: “=IF(E4="+","+",IF(ISBLANK(E4)," ","-"))”
- Minimum column: “=IF(ISBLANK(E4)," ",IF(K4="-",-E4/2,+E4/2))”

Insert the information here			
Part #	Stack Contributor	Tolerance Type	Tolerance Value

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
Total			0		0	0
Final Result				0	±	0

Figure 10: Screenshot of runout and concentricity automate tolerance chart file

4.3 Pseudo test case and results

For a quick verification, the following pseudo test case was performed. If the user entered the information from Table 6 then the 1D tolerance chart shown in Table 7 was expected.

Table 6: Runout and concentricity pseudo test user inputs

User Input	
Geometrical Tolerance Value	3

Table 7: Runout and concentricity pseudo test expected 1-D tolerance chart

Expected 1-D Tolerance Chart				
Sign	**Maximum**	**Sign**	**Minimum**	**Δ**
+	+1.5	-	-1.5	3

Then the same user input as listed in Table 6 was inserted in the runout and concentricity file and the automated tolerance chart was generated as seen in Figure 11.

Insert the information here			
Part #	Stack Contributor	Tolerance Type	Tolerance Value
	a	Circular Runout	3

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
	a	+	1.5	-	-1.5	3
Total			1.5		-1.5	3
Final Result				0	±	1.5

Figure 11: Screenshot of runout and concentricity pseudo test automated tolerance chart

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the expected 1-D chart results. Hence, verifying the logic of the program.

4.4 Test case and results

After the pseudo case was successfully executed, an actual test case was performed to verify the file developed. The test case conducted was from [Krulikowski, p 6-3].

The example mentioned in [Krulikowski, p 6-3] consists of size dimension as well. Hence, the size dimension file was combined with runout and concentricity file and a final result sheet was made as shown in Figure 17. In the final result sheet, the sum of maximum, minimum and tolerance columns were added to obtain the final results.

Figure 12: Screenshot of runout & concentricity and size & basic dimension combined files

Based on the stack path, the information was entered as shown in Figure 13 for size dimension and the automated chart was generated as shown in Figure 14.

Insert the information here					
Part #	Stack Contributor	Tolerance Type	Direction of Travel	Nominal Dimension	Tolerance Value
	C	Size Dimension	+	5.2	0.1
	A	Size Dimension	-	2.2	0.1

Figure 13: Screenshot of size & basic dimension file test case user inputs

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
	C	+	5.3	+	5.1	0.2
	A	-	-2.1	-	-2.3	0.2

Figure 14: Screenshot of size & basic dimension file test case automated tolerance chart

Then, the information was entered as shown in Figure 15 for runout and the automated chart was generated as shown in Figure 16.

Insert the information here			
Part #	Stack Contributor	Tolerance Type	Tolerance Value
	C	Circular Runout	0.3

Figure 15: Screenshot of runout & concentricity file test case user inputs

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
	C	+	0.15	-	-0.15	0.3

Figure 16: Screenshot of runout & concentricity file test case automated tolerance chart

Final Result		
Total Maximum	Total Minimum	Δ
3.35	2.65	0.7
OR		
3	±	0.35

Figure 17: Screenshot of test case final result

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the manual 1-D chart results. Thus, verifying the runout and concentricity file.

4.5 File limitation

Due to the simplicity of the rule and with just one user input, the runout and concentricity file has no known limitations so far.

CHAPTER 5: Development of Profile Individual File

5.1 Development of pseudocode

The profile rules comprises of two geometric characteristics: profile of a line and profile of a surface and follows 6 rules.

Rule #5: If there is no datum in the profile feature frame, then it is not used in the stack

Rule #6: For equal bilateral profile tolerance, first sign column is positive and second sign column is negative and half of geometrical tolerance value is entered in both maximum and minimum columns.

Rule #7: For unilateral profile tolerance, if direction of travel is +ve, both sign columns is +ve. The geometrical tolerance value is entered in maximum column and zero in minimum Column.

Rule #8: For unilateral profile tolerance, if direction of travel is -ve, both sign columns is -ve. The geometrical tolerance value is entered in minimum column and zero in maximum column.

Rule #9: For unequal bilateral, if direction of travel is +ve, both sign columns is +ve. The greater specified portion is entered in maximum column and the other portion in the minimum column

Rule #10: For unequal bilateral, if direction of travel is -ve, both sign columns is -ve. The greater specified portion is entered in minimum column and the other portion in the maximum column

Based on the six rules mentioned above, the following six user inputs would be required to perform the chart automatically:

- Any datum?: This is a drop down menu with two options: Yes and No

- Direction of travel (DT): This is a drop down menu with two options: + and -
- Nominal dimension (ND): Here, the user enters the nominal size dimension associated with the profile tolerance.
- + Tolerance value (+TV): Here, the user enters the + tolerance size value associated with the profile tolerance.
- - Tolerance value (-TV): Here, the user enters the – tolerance size value associated with the profile tolerance.
- Geometrical tolerance value (GTV): Here, the user enters the geometrical profile tolerance value

Once the rules and user inputs were comprehended, a pseudocode was written to detail the logic from the rules in programming language of "If and Else". The pseudocodes were written based on the user inputs for each of the four columns in 1D chart:

Left sign column (LSC)

If (No Datum)

Then (LSC = "N/A")

Else If (DT = Blank)

Then (LSC = " ")

Else If (|+TV|=|-TV|)

Then (LSC = "+")

Else (LSC = DT)

Maximum column (MAXC)

If (No Datum)

Then (MAXC = "N/A")

Else If (DT = Blank)

Then (MAXC = “ “)

Else If (|+TV|=|-TV|)

Then (MAXC = GTV/2)

Else If (|+TV|=0 OR |-TV|=0 && DT = “+”)

Then (MAXC = GTV)

Else If (|+TV|=0 OR |-TV|=0 && DT = “-”)

Then (MAXC = 0)

Else If (|+TV| ≠ |-TV| && |+TV| < |-TV| &&$\frac{|+TV|}{|-TV|} <$ 0.5&& DT = “+”)

Then {MAXC = GTV - ($\frac{|+TV|}{|-TV|} * GTV$)}

Else If (|+TV| ≠ |-TV| && |+TV| < |-TV| &&$\frac{|+TV|}{|-TV|} <$ 0.5&& DT = “-”)

Then {MAXC = -($\frac{|+TV|}{|-TV|} * GTV$)}

Else If (|+TV| ≠ |-TV| && |+TV| < |-TV| &&$\frac{|+TV|}{|-TV|} >$ 0.5&& DT = “+”)

Then {MAXC = ($\frac{|+TV|}{|-TV|} * GTV$)}

Else If (|+TV| ≠ |-TV| && |+TV| < |-TV| &&$\frac{|+TV|}{|-TV|} >$ 0.5&& DT = “-”)

Then [MAXC = $-\{GTV - (\frac{|+TV|}{|-TV|} * GTV)\}$]

Else If (|+TV| ≠ |-TV| && |+TV| > |-TV| &&$\frac{|-TV|}{|+TV|} <$ 0.5&& DT = “+”)

Then {MAXC = $GTV - (\frac{|-TV|}{|+TV|} * GTV)$}

Else If (|+TV| ≠ |-TV| && |+TV| > |-TV| &&$\frac{|-TV|}{|+TV|} <$ 0.5&& DT = “-”)

Then {MAXC = $-(\frac{|-TV|}{|+TV|} * GTV)$}

Else If (|+TV| ≠ |-TV| && |+TV| > |-TV| &&$\frac{|-TV|}{|+TV|} >$ 0.5&& DT = "+")

Then (MAXC = $\frac{|-TV|}{|+TV|} * GTV$)

Else If (|+TV| ≠ |-TV| && |+TV| > |-TV| &&$\frac{|-TV|}{|+TV|} >$ 0.5&& DT = "-")

Then [MAXC = $-\{GTV - (\frac{|-TV|}{|+TV|} * GTV)\}$]

Right sign column (RSC)

If (No Datum)

Then (RSC = "N/A")

Else If (DT = Blank)

Then (RSC = " ")

Else If (|+TV|=|-TV|)

Then (RSC = "-")

Else (RSC = DT)

Minimum column (MINC)

If (No Datum)

Then (MINC = "N/A")

Else If (DT = Blank)

Then (MINC = " ")

Else If (|+TV|=|-TV|)

Then (MINC = -GTV/2)

Else If (|+TV|=0 OR |-TV|=0 && DT = "+")

Then (MINC = 0)

Else If (|+TV|=0 OR |-TV|=0 && DT = "-")

Then (MINC = -GTV)

Else If (|+TV| ≠ |-TV| && |+TV| < |-TV| && $\frac{|+TV|}{|-TV|} <$ 0.5&& DT = "+")

Then {MINC = $\frac{|+TV|}{|-TV|} * GTV$)}

Else If (|+TV| ≠ |-TV| && |+TV| < |-TV| && $\frac{|+TV|}{|-TV|} <$ 0.5&& DT = "-")

Then [MINC = {$-GTV - (\frac{|+TV|}{|-TV|} * GTV)$ }]

Else If (|+TV| ≠ |-TV| && |+TV| < |-TV| && $\frac{|+TV|}{|-TV|} >$ 0.5&& DT = "+")

Then {MINC = $GTV - (\frac{|+TV|}{|-TV|} * GTV)$}

Else If (|+TV| ≠ |-TV| && |+TV| < |-TV| && $\frac{|+TV|}{|-TV|} >$ 0.5&& DT = "-")

Then {MINC = $-(\frac{|+TV|}{|-TV|} * GTV)$}

Else If (|+TV| ≠ |-TV| && |+TV| > |-TV| && $\frac{|-TV|}{|+TV|} <$ 0.5&& DT = "+")

Then {MINC = $(\frac{|-TV|}{|+TV|} * GTV)$}

Else If (|+TV| ≠ |-TV| && |+TV| > |-TV| && $\frac{|-TV|}{|+TV|} <$ 0.5&& DT = "-")

Then [MINC = {$-GTV - (\frac{|-TV|}{|+TV|} * GTV)$}]

Else If (|+TV| ≠ |-TV| && |+TV| > |-TV| && $\frac{|-TV|}{|+TV|} >$ 0.5&& DT = "+")

Then {MINC = $GTV - (\frac{|-TV|}{|+TV|} * GTV$}

Else If (|+TV| ≠ |-TV| && |+TV| > |-TV| && $\frac{|-TV|}{|+TV|} >$ 0.5&& DT = "-")

Then {MINC = $-(\frac{|-TV|}{|+TV|} * GTV)$}

5.2 Development of MS Excel file

The pseudocode was then transferred to MS Excel syntax and the file (Figure 18) was completed. Similar to previous two files, the user enters the information in the table on the left and the automated chart is generated on the right of the sheet. The cell numbers in MS Excel for the different user inputs are as follows –

2. Any datum? : E5
3. Direction of travel: F5
4. Nominal dimension: G5
5. + Tolerance value: H5
6. - Tolerance value: I5
7. Geometrical tolerance value: J5

The lines of code written in MS Excel for each of the four column are as follows –

- Left sign column: “=IF(E5="No","N/A",IF(ISBLANK(F5)," ",IF(H5=I5,"+",F5)))”
- Maximum column: “=IF(E5="No","N/A",IF(ISBLANK(F5)," ",IF(H5=I5,J5/2,IF(OR(H5=0,I5=0),IF(F5="+",J5,0),IF(H5<>I5,IF(H5<I5,IF(H5/I5<1/2, IF(F5="+",J5-(H5/I5*J5),-(H5/I5*J5)),IF(F5="+",H5/I5*J5,-(J5-(H5/I5*J5)))),IF(I5/H5<1/2,IF(F5="+",J5-(I5/H5*J5),-(I5/H5*J5)),IF(F5="+",I5/H5*J5,-(J5-(I5/H5*J5))))),” ")))))”
- Right sign column: “=IF(E5="No","N/A",IF(ISBLANK(F5)," ",IF(H5=I5,"-",F5)))”
- Minimum column: “ =IF(E5="No","N/A",IF(ISBLANK(F5)," ",IF(H5=I5,-J5/2,IF(OR(H5=0,I5=0),IF(F5="+",0,-J5),IF(H5<>I5,IF(H5<I5,IF(H5/I5<1/2,IF(F5="+",H5/I5*J5,-(J5-

(H5/I5*J5))),IF(F5="+",J5-H5/I5*J5,-(H5/I5*J5))),IF(I5/H5<1/2,IF(F5="+",I5/H5*J5,-(J5-(I5/H5*J5))),IF(F5="+",J5-I5/H5*J5,-(I5/H5*J5))))," ")))))”

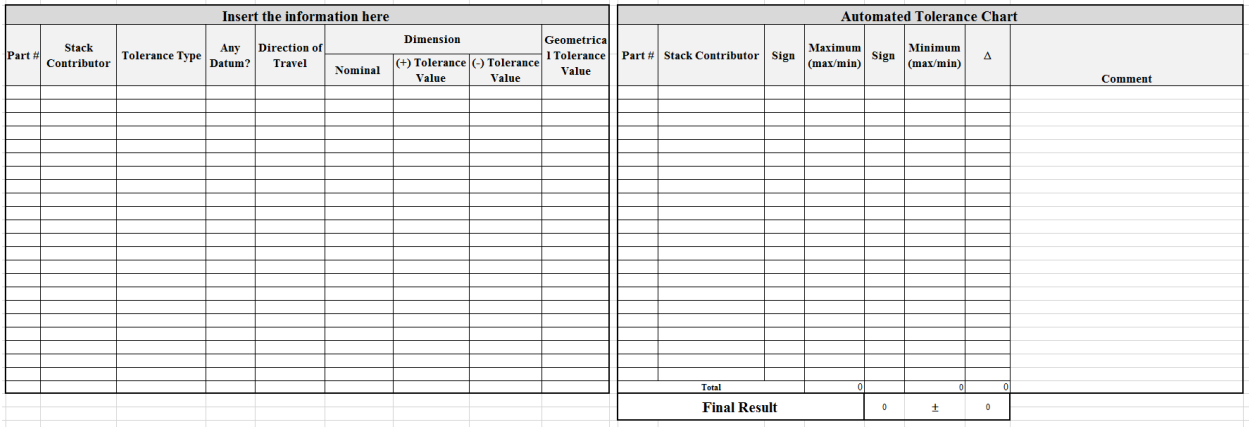


Figure 18: Screenshot of automated profile tolerance chart

5.3 Pseudo test case and results

For a quick verification, the following pseudo test case was performed. If the user entered the information from Table 8 then the 1D tolerance chart shown in Table 9 was expected.

Table 8: Profile pseudo test user inputs

User Inputs						
Sl. No.	**Any Datum?**	**Direction of Travel**	**Nominal Dimension**	**+ Tolerance Value**	**-Tolerance Value**	**Geometrical Tolerance Value**
1	No	-	-	-	-	-
2	Yes	+	5	3	3	2
3	Yes	-	5	3	3	2
4	Yes	+	5	3	0	2
5	Yes	-	5	0	3	2
6	Yes	+	5	3	10	2
7	Yes	-	5	3	10	2
8	Yes	+	5	10	3	2

9	Yes	-	5	10	3	2
10	Yes	+	5	3	5	2
11	Yes	-	5	3	5	2
12	Yes	+	5	5	3	2
13	Yes	-	5	5	3	2

Table 9: Profile pseudo test expected 1-D tolerance chart

Expected 1-D Tolerance Chart					
Sl. No.	**Sign**	**Maximum**	**Sign**	**Minimum**	**Δ**
1	N/A	N/A	N/A	N/A	N/A
2	+	1	-	-1	2
3	+	1	-	-1	2
4	+	2	+	0	2
5	-	0	-	-2	2
6	+	1.4	+	0.6	0.8
7	-	-0.6	-	-1.4	0.8
8	+	1.4	+	0.6	0.8
9	-	-0.6	-	-1.4	0.8
10	+	1.2	+	0.8	0.4
11	-	-0.8	-	-1.2	0.4
12	+	1.2	+	0.8	0.4
13	-	-0.8	-	-1.2	0.4
Total		6.4		-6.4	12.8

Then the same user input as listed in Table 8 was inserted in the profile file as seen in Figure 19 and the automated tolerance chart was generated as evident from Figure 20.

Insert the information here								
Part #	Stack Contributor	Tolerance Type	Any Datum?	Direction of Travel	Dimension			Geometrical Tolerance Value
					Nominal	(+) Tolerance Value	(-) Tolerance Value	
			No					
			Yes	+	5	3	3	2
			Yes	-	5	3	3	2
			Yes	+	5	3	0	2
			Yes	-	5	0	3	2
			Yes	+	5	3	10	2
			Yes	-	5	3	10	2
			Yes	+	5	10	3	2
			Yes	-	5	10	3	2
			Yes	+	5	3	5	2
			Yes	-	5	3	5	2
			Yes	+	5	5	3	2
			Yes	-	5	5	3	2

Figure 19: Screenshot of profile pseudo test user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
		N/A	N/A	N/A	N/A	N/A	Since no datum, profile tolerance cannot be used in the stack
		+	1	-	-1	2	
		+	1	-	-1	2	
		+	2	+	0	2	
		-	0	-	-2	2	
		+	1.4	+	0.6	0.8	
		-	-0.6	-	-1.4	0.8	
		+	1.4	+	0.6	0.8	
		-	-0.6	-	-1.4	0.8	
		+	1.2	+	0.8	0.4	
		-	-0.8	-	-1.2	0.4	
		+	1.2	+	0.8	0.4	
		-	-0.8	-	-1.2	0.4	
Total			6.4		-6.4	12.8	
Final Result				0	±	6.4	

Figure 20: Screenshot of profile pseudo test automated tolerance chart

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the expected 1-D chart results. Hence, verifying the logic of the program.

5.4 Test case and results

After the pseudo case was successfully executed, an actual test case was conducted from [Krulikowski, p 8-4] to verify the file developed.

As evident from [Krulikowski, p 8-4], the profile test like the runout test consists of certain size dimensions. Hence, the same procedure of adding a size and basic dimension sheet and final result sheet was done to successfully execute this test.

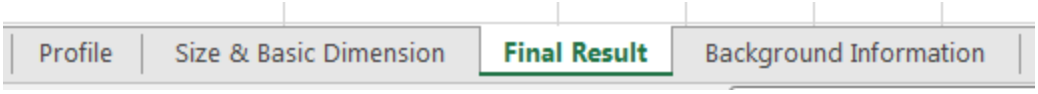


Figure 21: Screenshot of profile and size & basic dimension combined files

Based on the stack path, the information was entered as shown in Figure 22 for basic dimension and its automated chart was generated as shown in Figure 23.

Insert the information here					
Part #	**Stack Contributor**	**Tolerance Type**	**Direction of Travel**	**Nominal Dimension**	**Tolerance Value**
	B	Basic Dimension	+	72	
	C	Basic Dimension	-	60.3	

Figure 22: Screenshot of size & basic dimension file test case user inputs

Automated Tolerance Chart						
Part #	**Stack Contributor**	**Sign**	**Maximum (max/min)**	**Sign**	**Minimum (max/min)**	**Δ**
	B	+	72	+	72	0
	C	-	-60.3	-	-60.3	0

Figure 23: Screenshot of size & basic dimension file test case automated tolerance chart

Then, the information was entered as shown in Figure 24 for profile tolerances and its automated chart was generated as shown in Figure 25.

Insert the information here								
Part #	**Stack Contributor**	**Tolerance Type**	**Any Datum?**	**Direction of Travel**	**Dimension**			**Geometrical Tolerance Value**
					Nominal	**(+) Tolerance Value**	**(-) Tolerance Value**	
	A	Surface Profile	Yes	+	72			2
	D	Surface Profile	Yes	-	60.3			0.2

Figure 24: Screenshot of profile file test case user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
		+	1	-	-1	2	
		+	0.1	-	-0.1	0.2	

Figure 25: Screenshot of profile file test case automated tolerance chart

Final Result		
Total Maximum	Total Minimum	Δ
12.8	10.6	2.2
OR		
11.7	±	1.1

Figure 26: Screenshot of test case final result

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the manual 1-D chart results. Thus, verifying the profile file.

5.5 File limitations

The profile tolerance file takes care of three different cases: unequal bilateral, equal bilateral and unilateral. As of now, the profile file has no known limitations.

CHAPTER 6: Development of Orientation and Form (not FOS) Individual File

6.1 Development of pseudocode

Orientation and form are two different types of tolerance classes. In total they comprises of 7 GD&T geometrical characteristics. There are two feature types possible in orientation and form geometry: Feature of size (FOS) and Not FOS. Chapter 5 comprises of not FOS file and Chapter 6 comprises of FOS file. The not FOS category comprises of the following three rules –

Rule #11: If the stack goes thru the part, form and orientation tolerance on non FOS are not included in the stack.

Rule #12: If the part is adjacent to mating then first sign column is positive and second sign column is negative. The geometrical tolerance value is entered in maximum column and zero in minimum column.

Rule #13: If the If the part is offset from mating then first sign column is positive and second sign column is negative. The geometrical tolerance value is entered in both maximum and minimum column.

The following 3 user inputs were determined to be required to perform 1-D chart automatically:

- To or thru stack?: A drop down menu with two options: To stack and Thru stack
- Mating condition: A drop down menu with two options: Adjacent and Offset
- Geometrical tolerance value: Here, the user enters the geometrical tolerance value

Once the rules and user inputs were comprehended, a pseudocode was written to detail the logic from the rules in programming language of "If and Else". The pseudocodes were written based on the user inputs for each of the four columns in 1D chart:

Left sign column (LSC)

If (Thru Stack)

Then (LSC = “N/A”)

Else If (MC=Blank)

Then (LSC = “ “)

Else (LSC = “+”)

Maximum column (MAXC)

If (Thru Stack)

Then (MAXC = “N/A”)

Else If (MC=Blank)

Then (MAXC = “ “)

Else (MAXC=+GTV)

Right sign column (RSC)

If (Thru Stack)

Then (RSC = “N/A”)

Else If (MC=Blank)

Then (RSC = “ “)

Else (RSC = “-”)

Minimum column (MINC)

If (Thru Stack)

Then (MINC = “N/A”)

Else If (MC=Blank)

Then (MINC = “ “)

Else If (MC= “Offset”)

Then (MINC = -GTV)

Else If (MC = “Adjacent”)

Then (MINC = 0)

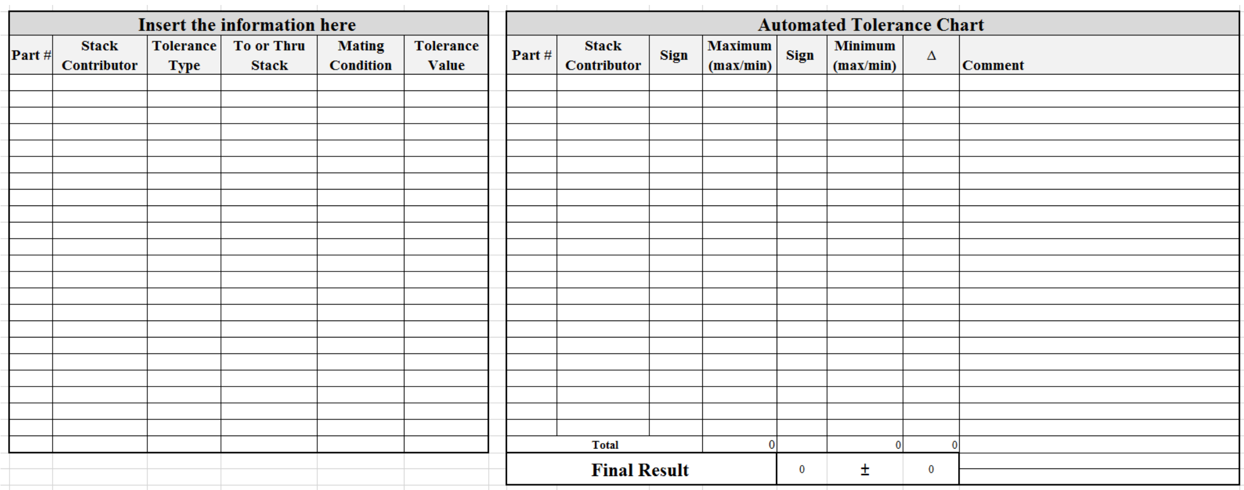
6.2 Development of MS Excel file

The pseudocode was then transferred to MS Excel syntax and the file (Figure 27) was completed. As it can be seen in Figure 27, the user enters the information in the table on the left and the automated chart is generated on the right of the sheet. The cell numbers in MS Excel for the different user inputs are as follows –

- To or thru stack?: E4
- Mating condition: F4
- Geometrical tolerance value: G4

The lines of code written in MS Excel for each of the four column are as follows –

- Left sign column: “=IF(E4="Thru stack","N/A",IF(ISBLANK(F4)," ","+"))”
- Maximum column: “=IF(E4="Thru stack","N/A",IF(F4="Offset",+H4,IF(ISBLANK(F4)," ",IF(F4="Adjacent",IF(G4="-",-H4,+H4))))) ”
- Right sign column: “=IF(E4="Thru stack","N/A",IF(ISBLANK(F4)," ","-")) ”
- Minimum column: “ =IF(E4="Thru stack","N/A",IF(F4="Offset",-H4,IF(ISBLANK(F4)," ",IF(F4="Adjacent",0,H4))))”



Insert the information here					
Part #	Stack Contributor	Tolerance Type	To or Thru Stack	Mating Condition	Tolerance Value

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
	Total		0		0	0	
	Final Result			0	±	0	

Figure 27: Screenshot of orientation and form (not FOS) automate tolerance chart file

6.3 Pseudo test case and results

For a quick verification, the following pseudo test case was performed. If the user entered the information from Table 10 then the 1D tolerance chart shown in Table 11 was expected.

Table 10: Orientation and form (not FOS) pseudo test user inputs

User Inputs			
Sl. No.	**To or Thru Stack**	**Mating Condition**	**Geometrical Tolerance Value**
1	Thru stack		
2	To stack	Adjacent	2
3	To stack	Offset	2

Table 11: Orientation and form (not FOS) pseudo test expected 1-D tolerance chart

Expected 1-D Tolerance Chart					
Sl. No.	**Sign**	**Maximum**	**Sign**	**Minimum**	**Δ**
1	N/A	N/A	N/A	N/A	N/A
2	+	2	-	0	2
3	+	2	-	-2	4

Total	4		-2	6

Then the same user input as listed in Table 10 was inserted in the orientation and form (not FOS) file as seen in Figure 28 and the automated tolerance chart was generated as evident from Figure 29.

Insert the information here					
Part #	**Stack Contributor**	**Tolerance Type**	**To or Thru Stack**	**Mating Condition**	**Geometrical Tolerance Value**
			Thru stack		
			To stack	Adjacent	2
			To stack	Offset	2

Figure 28: Screenshot of orientation and form (not FOS) pseudo test user inputs

Automated Tolerance Chart							
Part #	**Stack Contributor**	**Sign**	**Maximum (max/min)**	**Sign**	**Minimum (max/min)**	**Δ**	**Comment**
		N/A	N/A	N/A	N/A	N/A	Since the stack goes thru, tolence not included in the stack
		+	2	-	0	2	
		+	2	-	-2	4	
Total			4		-2	6	
Final Result				1	±	3	

Figure 29: Screenshot of orientation and form (not FOS) pseudo test automated tolerance chart

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the expected 1-D chart results. Hence, verifying the logic of the program.

6.4 Test case # 1 and results

As orientation and form (not FOS) comprises of two different tolerance classes, two test cases were performed on this file. The first test comprised of geometric characteristic from form tolerance class: flatness. The second test comprised of geometric characteristic from both form

and orientation tolerance class: flatness and parallelism. For both the test cases, [Krulikowski, p 16-3] comprises of the part's geometric and dimension variations. The test case conducted was from [Krulikowski, p 16-5].

Like profile and runout & concentricity tests, the orientation & form (not FOS) test comprised of size and basic dimensions. Hence, the two files were combined and one final result sheet was made to perform the tolerance analysis test. Based on the stack path, the information for size dimension was entered as shown in Figure 30 and the automated chart for size dimension was generated as shown in Figure 31.

Insert the information here					
Part #	**Stack Contributor**	**Tolerance Type**	**Direction of Travel**	**Nominal Dimension**	**Tolerance Value**
P1000		Size Dimension	+	12.53	0.03
P1003		Size Dimension	-	1.01	0.01
P1002		Size Dimension	-	11.41	0.01

Figure 30: Screenshot of size and basic dimension test #1 user inputs

Automated Tolerance Chart						
Part #	**Stack Contributor**	**Sign**	**Maximum (max/min)**	**Sign**	**Minimum (max/min)**	**Δ**
P1000		+	12.56	+	12.5	0.06
P1003		-	-1	-	-1.02	0.02
P1002		-	-11.4	-	-11.42	0.02

Figure 31: Screenshot of size and basic dimension test #1 automated tolerance chart

Then, the information for flatness was entered as shown in Figure 32 and the automated chart for flatness was generated as shown in Figure 33.

Insert the information here						
Part #	Stack Contributor	Tolerance Type	To or Thru Stack	Mating Condition	Direction of Travel	Tolerance Value
P1001		Flatness	To stack	Offset	+	0.03
P1000		Flatness	Thru stack			
P1003		Flatness	Thru stack			

Figure 32: Screenshot of orientation and form (not FOS) test #1 user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
P1001		+	0.03	-	-0.03	0.06	
P1000		N/A	N/A	N/A	N/A	N/A	Since the stack goes thru, tolence not included in the stack
P1003		N/A	N/A	N/A	N/A	N/A	Since the stack goes thru, tolence not included in the stack

Figure 33: Screenshot of orientation and form (not FOS) test #1 automated tolerance chart

Final Result		
Total Maximum	Total Minimum	Δ
0.19	0.03	0.16
OR		
0.11	±	0.08

Figure 34: Screenshot of test #1 final result

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the manual 1D chart results. Thus, verifying the orientation and form (not FOS) file.

6.5 Test case # 2 and results

The second test case comprised of the same assembly but now the geometric area of interest of this assembly is the gap between the cover and the housing, can be found in [Krulikowski, p 14-7]. The geometric dimensions and variations of the part is shown in [Krulikowski, p 16-3].

Based on the part drawings, the information was entered as shown in Figure 35 and the automated chart was generated as shown in Figure 36.

Insert the information here						
Part #	Stack Contributor	Tolerance Type	To or Thru Stack	Mating Condition	Direction of Travel	Tolerance Value
P1001		Flatness	To stack	Adjacent	+	0.03
P1005		Parallelism	To stack	Adjacent	+	0.02

Figure 35: Screenshot of orientation and form (not FOS) test #2 user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
P1001		+	0.03	-	0	0.03	
P1005		+	0.02	-	0	0.02	

Figure 36: Screenshot of orientation and form (not FOS) test #2 automated tolerance chart

Final Result		
Total Maximum	Total Minimum	Δ
0.05	0	0.05
OR		
0.025	±	0.025

Figure 37: Screenshot of orientation and form (not FOS) test #2 final result

For both the test cases, the total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the manual 1-D chart results. Thus, verifying the orientation and form (not FOS) file.

6.6 File limitations

With both the rules conditions taken care of, orientation and form (not FOS) has no known limitations.

CHAPTER 7: Development of Orientation, Straightness and Cylindricity (FOS) Individual File

7.1 Development of pseudocode

This section comprises of rules applied to FOS. These following four rules can be applied to all the four orientation geometric characteristics but only to two form geometric characteristics: straightness and cylindricity.

Rule #14: If direction of travel is +ve, enter +ve in both sign columns. If it is an FOS internal part, enter LMC of size in maximum column and VC of size in minimum column.

Rule #15: If direction of travel is -ve, enter -ve in both sign columns. If it is an FOS internal part, enter VC of size in maximum column and LMC of size in minimum column.

Rule #16: If direction of travel is +ve, enter + in both sign columns. If it is an FOS external part, enter VC of size in maximum column and LMC in minimum column.

Rule #17: If direction of travel is -ve, enter - in both sign columns. If it is an FOS external part, enter LMC of size in maximum column and VC of size in minimum column.

According to the rules, the following five user inputs were deemed necessary to perform the 1-D chart automatically:

- Direction of travel (DT): A drop down menu with two options: + and -
- Internal or external part: A drop down menu with two options: internal and external
- Nominal dimension (ND): Here, the user enters the nominal size dimension
- Tolerance value (TV): Here, the user enters the size tolerance value
- Geometrical tolerance value (GTV): Here, the user enters the geometrical tolerance value.

Apart from the rules above, these following six formulae are required to perform 1-D tolerance chart successfully:

- For internal part:
    - MMC = ND - TV
    - LMC = ND + TV
    - VC = MMC - GTV
- For external part:
    - MMC = ND + TV
    - LMC = ND - TV
    - VC = LMC – GTV

Once the rules and user inputs were comprehended, a pseudocode was written to detail the logic from the rules in programming language of "If and Else". The pseudocodes were written based on the user inputs for each of the four columns in 1D chart:

Left sign column (LSC)

If (DT = Blank)

Then (LSC = " ")

Else If (DT="+")

Then (LSC="+")

Else (LSC = "-")

Maximum column (MAXC)

If (DT=Blank)

Then (MAXC=" ")

Else If (Internal Part && DT="+")

Then (MAXC=ND+TV)

Else If (Internal Part && DT="-")

Then (MAXC=-(ND-TV-GTV))

Else If (External Part && DT=”+”)

Then (MAXC=ND+TV+GTV)

Else If (External Part && DT=”-”)

Then (MAXC=-(ND-TV))

Right sign column (RSC)

If (DT = Blank)

Then (LSC = “ “)

Else If (DT=”+”)

Then (LSC=”+”)

Else (LSC = ”-”)

Minimum column (MINC)

If (DT=Blank)

Then (MINC=” “)

Else If (Internal Part && DT=”+”)

Then (MINC=ND-TV-GTV)

Else If (Internal Part && DT=”-”)

Then (MINC=-(ND+TV))

Else If (External Part && DT=”+”)

Then (MINC=ND-TV)

Else If (External Part && DT=”-”)

Then (MINC=-(ND+TV+GTV))

7.2 Development of MS Excel file

The pseudocode was then transferred to MS Excel syntax and the file (Figure 38) was completed. As it can be seen in Figure 43 like all the other individual files, the user enters the information in the table on the left and the automated chart is generated on the right side of the sheet. The cell numbers in MS Excel for the different user inputs are as follows –

- Direction of travel: E5
- Internal or external: F5
- Nominal dimension: G5
- Tolerance value: H5
- Geometrical tolerance value: I5

The lines of code written in MS Excel for each of the four column are as follows –

- Left sign column: “ =IF(E4="Thru stack","N/A",IF(ISBLANK(F4)," ","+"))”
- Maximum column: “ =IF(E4="Thru stack","N/A", IF(F4="Offset",+H4, IF(ISBLANK(F4)," ", IF(F4="Adjacent",IF(G4="-",-H4,+H4)))))”
- Right sign column: “ =IF(E4="Thru stack","N/A",IF(ISBLANK(F4)," ","-"))”
- Minimum column: “ =IF(E4="Thru stack","N/A",IF(F4="Offset",-H4, IF(ISBLANK(F4)," ", IF(F4="Adjacent",0,H4))))”

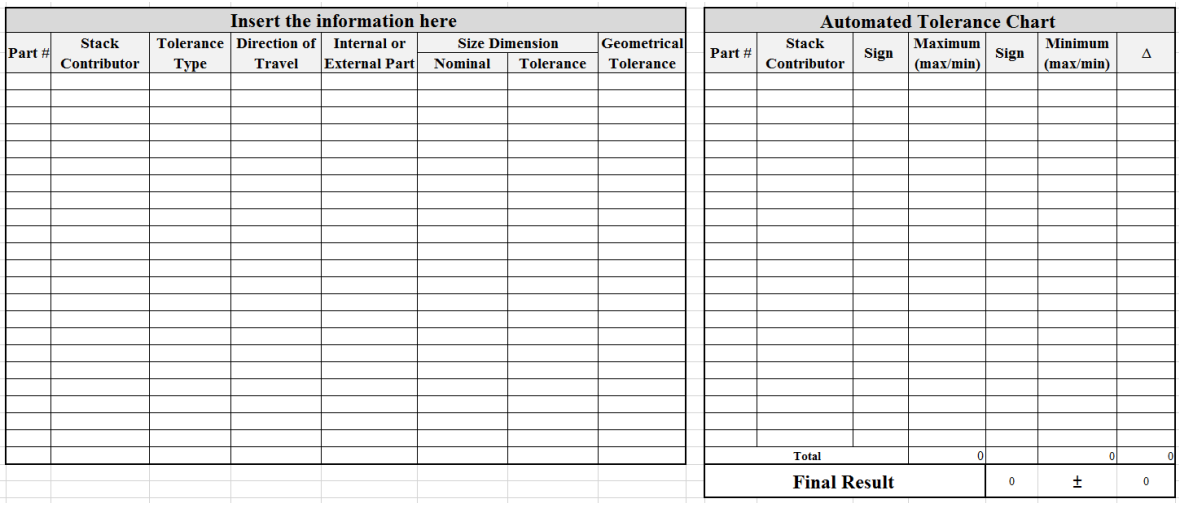


Figure 38: Screenshot of orientation and form (FOS) automate tolerance chart file

7.3 Pseudo test case and results

For a quick verification, the following pseudo test case was performed. If the user entered the information from Table 12 then the 1D tolerance chart shown in Table 13 was expected.

Table 12: Orientation and form (FOS) pseudo test user inputs

User Inputs					
Sl. No.	**Direction of Travel**	**Internal or External Part**	**Nominal Dimension**	**Tolerance Value**	**Geometrical Tolerance Value**
1	+	Internal	10	3	2
2	-	Internal	10	3	2
3	+	External	10	3	2
4	-	External	10	3	2

Table 13: Orientation and form (FOS) pseudo test expected 1-D tolerance chart

Expected 1-D Tolerance Chart					
Sl. No.	**Sign**	**Maximum**	**Sign**	**Minimum**	**Δ**
1	+	13	+	5	8
2	-	-5	-	-13	8

3	+	15	+	7	8
4	-	-7	-	-15	8
Total		16		-16	32

Then the same user input as listed in Table 12 was inserted in the orientation and form (not FOS) file as seen in Figure 39 and the automated tolerance chart was generated as evident from Figure 40.

Insert the information here							
Part #	Stack Contributor	Tolerance Type	Direction of Travel	Internal or External Part	Size Dimension		Geometrical Tolerance
					Nominal	Tolerance	
			+	Internal	10	3.00	2
			-	Internal	10	3.00	2
			+	External	10	3.00	2
			-	External	10	3.00	2

Figure 39: Screenshot of orientation and form (FOS) pseudo test user inputs

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
		+	13	+	5	8
		-	-5	-	-13	8
		+	15	+	7	8
		-	-7	-	-15	8
Total			16		-16	32
Final Result				0	±	16

Figure 40: Screenshot of orientation and form (FOS) pseudo test automated tolerance chart

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the expected 1-D chart results. Hence, verifying the logic of the program.

7.4 Test case #1 and results

As orientation and form (FOS) also comprises of two different tolerance classes, two test cases were performed on this file. The first test comprised of geometric characteristic from form tolerance class: straightness. The second test comprised of geometric characteristic from orientation tolerance class: perpendicularity. The test case can be found in [Krulikowski, p 15-5] with its part dimensions mentioned in [Krulikowski, p 15-3].

Based on the stack path, the information was entered as shown in Figure 41 and the automated chart was generated as shown in Figure 42.

Insert the information here							
Part #	Stack Contributor	Tolerance Type	Direction of Travel	Internal or External Part	Size Dimension		Geometrical Tolerance
					Max Value	Min Value	
X481		Size Dimension	+	Internal	15.9	15.60	
X482		Straightness	-	External	2.80	2.60	0.3
X482		Straightness	-	External	2.80	2.60	0.3
X482		Straightness	-	External	2.80	2.60	0.3
X482		Straightness	-	External	2.80	2.60	0.3
X482		Straightness	-	External	2.80	2.60	0.3

Figure 41: Screenshot of orientation and form (FOS) test #1 user inputs

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
X481		+	15.9	+	15.6	0.3
X482		-	-2.6	-	-3.1	0.5
X482		-	-2.6	-	-3.1	0.5
X482		-	-2.6	-	-3.1	0.5
X482		-	-2.6	-	-3.1	0.5
X482		-	-2.6	-	-3.1	0.5
Total			2.9		0.1	2.8
Final Result				1.5	±	1.4

Figure 42: Screenshot of orientation and form (FOS) test #1 automated tolerance chart

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the manual results. Thus, verifying the orientation and form (FOS) file.

7.5 Test case #2 and results

As mentioned before, the second test comprised of geometric characteristic from orientation tolerance class: perpendicularity. The test case can be found in [Krulikowski, p 17-4] with its part dimensions in [Krulikowski, p 17-3].

Based on the stack path, the information was entered as shown in Figure 43 and the automated chart was generated as shown in Figure 44.

Insert the information here							
Part #	Stack Contributor	Tolerance Type	Direction of Travel	Internal or External Part	Size Dimension		Tolerance Value
					Max Value	Min Value	
P1007		Perpendicularity	-	External	60.05	60.00	0.05
P1005		Perpendicularity	+	Internal	60.30	60.20	0.05

Figure 43: Screenshot of orientation and form (FOS) test #2 user inputs

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
P1007		-	-60	-	-60.1	0.1
		+	60.3	+	60.15	0.15
Total			0.3		0.05	0.25
Final Result				0.175	±	0.125

Figure 44: Screenshot of orientation and form (FOS) test #2 automated tolerance chart

For both the test cases, the total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the manual 1-D chart results. Thus, verifying the orientation, straightness and cylindricity (FOS) file.

7.6 File limitations

With both the part type: external and internal conditions taken care of, orientation, straightness and cylindricity (FOS) has no known limitations.

CHAPTER 8: Development of Position Individual File

8.1 Development of pseudocode

Position tolerance has the maximum number of rules and the most complex rules. Each entry in position tolerance row results in subsequent following three rows in the 1-D chart:

1. Position tolerance row
2. Bonus row
3. Shift row

And each of the above mentioned rows follow different rules for maximum and minimum column but the same for sign columns. Hence the rules have been mentioned here based on these three rows:

Rule for sign columns:

Rule #18: For each row, regardless of user inputs, first sign column is positive and second sign column is negative always

Rule for position tolerance row:

Rule #19: Half the geometrical tolerance value is entered in both maximum and minimum columns.

Rules for bonus row:

Rule #20: If it is a press fit then maximum radial bonus is entered in both maximum and minimum columns

Rule #21: If it is not a press fit and LMC or MMC modifier is used as a tolerance modifier, then zero bonus is entered in the column containing the MMC radius and maximum radial bonus is entered in the column containing the LMC radius

Rules for shift row:

Rule #22: If it is a press fit and there is a MMC or LMC modifier used as a datum modifier, then maximum shift is entered in both maximum and minimum columns

Rule #23: If it is not a press fit and there is a MMC or LMC modifier used as a datum modifier, then minimum shift is entered in the column containing the MMC radius of the datum and maximum shift is entered in the column containing the LMC radius of the datum

Apart from the rules above, these following four formulae are required to perform 1-D tolerance chart successfully:

- For internal part:
    - Maximum shift = LMC - VC
    - Minimum shift = MMC - VC
- For external part:
    - Maximum shift = VC - LMC
    - Minimum shift = VC - MMC

According to the rules, the following 11 user inputs were deemed necessary to perform the 1-D chart automatically:

- Press fit: A drop down menu with two options: Yes and No
- Internal or external part: A drop down menu with two options: Internal and External
- Direction of travel: A drop down menu with two options: + and -
- Nominal dimension: Here, the user enters the nominal size dimension associated with the geometrical tolerance.
- Tolerance value: Here, the user enters the size tolerance value
- Geometrical tolerance value: Here, the user enters the geometrical tolerance value.
- Tolerance modifier: A drop down menu with two options: MMC and LMC

- Datum modifier details
    - Datum modifier: A drop down men with two options: MMC and LMC
    - Nominal Dimension: Here, the user enters the nominal size dimension associated with the datum that has either a MMC or LMC modifier
    - Tolerance Value: The user enters the size tolerance value associated with the datum that has either a MMC or LMC modifier
    - Geometrical Tolerance Value: Here, the user enters the geometrical tolerance value associated with the datum that has either a MMC or LMC modifier

Once the rules and user inputs were comprehended, a pseudocode was written to detail the logic from the rules in programming language of "If and Else". The pseudocodes were written based on the user inputs for each of the four columns in 1D chart:

<u>Left sign column (Position row)</u>

If (TT=Blank)

Then (LSC = " ")

Else (LSC = "+")

<u>Maximum column (Position row)</u>

If (DT = Blank)

Then (MAXC = " ")

Else (MAXC = TV/2)

<u>Right sign column (Position row)</u>

If (TT=Blank)

Then (RSC = " ")

Else (RSC = "-")

Minimum column (Position Row)

If (DT = Blank)

Then (MINC = " ")

Else (MINC = -TV/2)

Left sign column (Bonus Row)

If (TT=Blank)

Then (LSC = " ")

Else (LSC = "+")

Maximum column (Bonus Row)

If (DT=Blank)

Then (MAXC = " ")

Else If (Press Fit)

Then (MAXC=2*TV)

Else If (MMC geometrical tolerance modifier && Internal part && DT = "+")

Then (MAXC=2*TV)

Else If (MMC geometrical tolerance modifier && Internal part && DT = "-")

Then (MAXC=0)

Else If (MMC geometrical tolerance modifier && External part && DT = "+")

Then (MAXC=0)

Else If (MMC geometrical tolerance modifier && External part && DT = "-")

Then (MAXC=2*TV)

Else If (LMC geometrical tolerance modifier && Internal part && DT = "+")

Then (MAXC=0)

Else If (LMC geometrical tolerance modifier && Internal part && DT = “-”)

Then (MAXC=2*TV)

Else If (LMC geometrical tolerance modifier && External part && DT = “+”)

Then (MAXC=2*TV)

Else If (LMC geometrical tolerance modifier && External part && DT = “-”)

Then (MAXC=0)

Right sign column (Bonus Row)

If (TT=Blank)

Then (RSC = “ “)

Else (RSC = “-”)

Minimum column (Bonus Row)

If (DT=Blank)

Then (MINC = “ “)

Else If (Press Fit)

Then (MINC=-2*TV)

Else If (MMC geometrical tolerance modifier && Internal part && DT = “+”)

Then (MINC=0)

Else If (MMC geometrical tolerance modifier && Internal part && DT = “-”)

Then (MINC=-2*TV)

Else If (MMC geometrical tolerance modifier && External part && DT = “+”)

Then (MINC=-2*TV)

Else If (MMC geometrical tolerance modifier && External part && DT = “-”)

Then (MINC=0)

Else If (LMC geometrical tolerance modifier && Internal part && DT = “+”)

Then (MINC=-2*TV)

Else If (LMC geometrical tolerance modifier && Internal part && DT = “-”)

Then (MINC=0)

Else If (LMC geometrical tolerance modifier && External part && DT = “+”)

Then (MINC=0)

Else If (LMC geometrical tolerance modifier && External part && DT = “-”)

Then (MINC=-2*TV)

Left sign column (Shift Row)

If (TT=Blank)

Then (LSC = “ “)

Else (LSC = “+”)

Maximum column (Shift Row)

If (DT=Blank)

Then (MAXC = “ “)

Else If (Press Fit && MMC datum modifier && Internal Part)

Then (MAXC = (ND(Datum)+TV(Datum))-(ND(Datum)-TV(Datum)-GTV(Datum)))

Else If (Press Fit && MMC datum modifier && External Part)

Then (MAXC = (ND(Datum)+TV(Datum)+GTV(Datum))-(ND(Datum)-TV(Datum)))

Else If (Press Fit && LMC datum modifier && Internal Part)

Then (MAXC = (ND(Datum)-TV(Datum))-(ND(Datum)-TV(Datum)-GTV(Datum)))

Else If (Press Fit && LMC datum modifier && External Part)

Then (MAXC = (ND(Datum)+TV(Datum)+GTV(Datum))-(ND(Datum)+TV(Datum)))

Else If (MMC datum modifier && Internal Part && DT=”+”)

Then (MAXC = (ND(Datum) + TV(Datum)) - (ND(Datum) - TV(Datum) - GTV(Datum)))

Else If (MMC datum modifier && Internal Part && DT=”-”)

Then (MAXC = (ND(Datum) - TV(Datum)) - (ND(Datum) - TV(Datum) - GTV(Datum)))

Else If (MMC datum modifier && External Part && DT=”+”)

Then (MAXC = (ND(Datum)+TV(Datum)+GTV(Datum)) - (ND(Datum) + TV(Datum)))

Else If (MMC datum modifier && External Part && DT=”-”)

Then (MAXC = (ND(Datum) + TV(Datum)+GTV(Datum)) - (ND(Datum) - TV(Datum)))

Else If (LMC datum modifier && Internal Part && DT=”+”)

Then (MAXC = (ND(Datum) - TV(Datum)) - (ND(Datum) - TV(Datum) - GTV(Datum)))

Else If (LMC datum modifier && Internal Part && DT=”-”)

Then (MAXC = (ND(Datum) + TV(Datum)) - (ND(Datum) - TV(Datum) - GTV(Datum)))

Else If (LMC datum modifier && External Part && DT=”+”)

Then (MAXC = (ND(Datum)+TV(Datum)+GTV(Datum)) - (ND(Datum) - TV(Datum)))

Else If (LMC datum modifier && External Part && DT=”-”)

Then (MAXC = (ND(Datum) + TV(Datum)+GTV(Datum)) - (ND(Datum) + TV(Datum)))

Right sign column (Shift Row)

If (TT=Blank)

Then (RSC = “ “)

Else (RSC = “-”)

Minimum column (Shift Row)

If (DT=Blank)

Then (MINC = “ “)

Else If (Press Fit && MMC datum modifier && Internal Part)

Then (MINC = -((ND(Datum)+TV(Datum))-(ND(Datum)-TV(Datum)-GTV(Datum))))

Else If (Press Fit && MMC datum modifier && External Part)

Then (MINC = (ND(Datum)-TV(Datum))-(ND(Datum)+TV(Datum)+GTV(Datum)))

Else If (Press Fit && LMC datum modifier && Internal Part)

Then (MINC = -((ND(Datum)-TV(Datum))-(ND(Datum)-TV(Datum)-GTV(Datum))))

Else If (Press Fit && LMC datum modifier && External Part)

Then (MINC = (ND(Datum)+TV(Datum))-(ND(Datum)+TV(Datum)+GTV(Datum)))

Else If (MMC datum modifier && Internal Part && DT=”+”)

Then (MINC = -((ND(Datum) - TV(Datum)) - (ND(Datum) - TV(Datum) -

GTV(Datum))))

Else If (MMC datum modifier && Internal Part && DT=”-”)

Then (MINC = -((ND(Datum) +TV(Datum)) - (ND(Datum) - TV(Datum) -

GTV(Datum))))

Else If (MMC datum modifier && External Part && DT=”+”)

Then (MINC = (ND(Datum)-TV(Datum)) - (ND(Datum) + TV(Datum)+GTV(Datum)))

Else If (MMC datum modifier && External Part && DT=”-”)

Then (MINC = (ND(Datum) + TV(Datum)) - (ND(Datum) + TV(Datum)+GTV(Datum)))

Else If (LMC datum modifier && Internal Part && DT=”+”)

Then (MINC = -((ND(Datum) + TV(Datum)) - (ND(Datum) - TV(Datum) - GTV(Datum))))

Else If (LMC datum modifier && Internal Part && DT=”-”)

Then (MINC = -((ND(Datum) - TV(Datum)) - (ND(Datum) - TV(Datum) - GTV(Datum))))

Else If (LMC datum modifier && External Part && DT=”+”)

Then (MINC = (ND(Datum)+TV(Datum)) - (ND(Datum) + TV(Datum)+GTV(Datum)))

Else If (LMC datum modifier && External Part && DT=”-”)

Then (MINC = (ND(Datum) - TV(Datum)) - (ND(Datum) + TV(Datum)+GTV(Datum)))

8.2 Development of MS Excel file

The pseudocode was then transferred to MS Excel syntax and the file (Figure 45 and 46) was completed. The user enters the information in the table shown in Figure 45 and the automated chart is generated as shown in Figure 46.

Insert the information here													
Part #	Stack Contributor	Press Fit?	Internal or External Part?	Direction of Travel	Dimension		Position tolerance details			Datum modifier details			
										Datum modifier	Dimension		
					Nominal	Tolerance	Tolerance Type	Tolerance Value	Tolerance Modifier		Nominal Dimension	Tolerance Value	Geometrical Tolerance Value

Figure 45: Screenshot of position user input file

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
							Position
							Bonus
							Shift
							Position
							Bonus
							Shift
							Position
							Bonus
							Shift
Total			0		0	0	
Final Result					0	±	0

Figure 46: Screenshot of position automate tolerance chart file

The cell numbers in MS Excel for the different user inputs are as follows –

- Press fit: D6
- Internal or external part: E6
- Direction of travel: F6
- Nominal dimension: G6
- Tolerance value: H6

- Geometrical tolerance value: J6
- Tolerance modifier: K6
- Datum modifier details
    - Datum modifier: L6
    - Nominal Dimension: M6
    - Tolerance Value: N6
    - Geometrical Tolerance Value: O6

The lines of code written in excel for each of the four column are as follows –

Position Row

- Left sign column: “=IF(ISBLANK(F6)," ","+") ”
- Maximum column: “ =IF(ISBLANK(F6)," ",+J6/2)”
- Right sign column: “=IF(ISBLANK(F6)," ","-") ”
- Minimum column: “=IF(ISBLANK(F6)," ",-J6/2) ”

Bonus Row

- Left sign column: “=IF(ISBLANK(F6)," ","+") ”
- Maximum column: “=IF(ISBLANK(F6)," ",IF(D6="Yes",2*H6,IF(K6="MMC",IF(E6="Internal",IF(F6="+",2*H6,0),IF(F6="+",0,2*H6)),IF(K6="LMC",IF(E6="Internal",IF(F6="+",0,2*H6),IF(F6="+",2*H6,0)),0)))) ”
- Right sign column: “=IF(ISBLANK(F6)," ","-") ”
- Minimum column: “ =IF(ISBLANK(F6)," ",IF(D6="Yes",-2*H6,IF(K6="MMC",IF(E6="Internal",IF(F6="+",0,-2*H6),IF(F6="+",-2*H6,0)),IF(K6="LMC",IF(E6="Internal",IF(F6="+",-2*H6,0),IF(F6="+",0,-2*H6)),0)))) ”

Shift Row

- Left sign column: “=IF(ISBLANK(F6)," ","+") ”
- Maximum column: “ =IF(ISBLANK(F6)," ", IF(D6="Yes", IF(E6="Internal",IF(OR(L6="MMC",L6="LMC"), IF(L6="MMC",(M6+N6)-(M6-N6-O6),(M6-N6)-(M6-N6-O6)),0), IF(OR(L6="MMC",L6="LMC"), IF(L6="MMC",(M6+N6+O6)-(M6-N6),(M6+N6+O6)-(M6+N6)),0)), IF(L6="MMC", IF(E6="Internal", IF(F6="+",(M6+N6)-(M6-N6-O6),(M6-N6)-(M6-N6-O6)), IF(F6="+",(M6+N6+O6)-(M6+N6),(M6+N6+O6)-(M6-N6))), IF(L6="LMC",IF(E6="Internal", IF(F6="+",(M6-N6)-(M6-N6-O6),(M6+N6)-(M6-N6-O6)), IF(F6="+",(M6+N6+O6)-(M6-N6),(M6+N6+O6)-(M6+N6))),0))))”
- Right sign column: “=IF(ISBLANK(F6)," ","-") ”
- Minimum column: “ =IF(ISBLANK(F6)," ", IF(D6="Yes", IF(E6="Internal", IF(OR(L6="MMC",L6="LMC"), IF(L6="MMC",-((M6+N6)-(M6-N6-O6)),-((M6-N6)-(M6-N6-O6))),0), IF(OR(L6="MMC",L6="LMC"), IF(L6="MMC",(M6-N6)-(M6+N6+O6),(M6+N6)-(M6+N6+O6)),0)),IF(L6="MMC",IF(E6="Internal", IF(F6="+",-((M6-N6)-(M6-N6-O6)),-((M6+N6)-(M6-N6-O6))), IF(F6="+",(M6-N6)-(M6+N6+O6),(M6+N6)-(M6+N6+O6))), IF(L6="LMC", IF(E6="Internal", IF(F6="+",-((M6+N6)-(M6-N6-O6)),-((M6-N6)-(M6-N6-O6))), IF(F6="+",(M6+N6)-(M6+N6+O6),(M6-N6)-(M6+N6+O6))),0))))”

8.3 Pseudo test case #1 and results (Position row)

The 1D tolerance chart of position file comprises of three rows of output for one row of data input. Hence, three different pseudo test cases were conducted to individually test each row. The position row has only one rule and thus one line of test case was sufficient for its validation.

For a quick verification, the following pseudo test case was performed. If the user entered the information from Table 14 then the 1D tolerance chart for position row shown in Table 15 was expected.

Table 14: Position pseudo test (Position row) user inputs

User Inputs											
Sl. No.	Press Fit?	Internal/ External Part	Direction of Travel	Dimension		Tolerance details		Datum modifier details			
				ND	TV	GTV	Modifier	Modifier	ND	TV	GTV
1			+			3					

Table 15: Position pseudo test (Position row) expected 1-D tolerance chart

Expected 1-D Tolerance Chart						
Sl. No.	Sign	Maximum	Sign	Minimum	Δ	Comment
1	+	1.5	-	-1.5	3	Position
Total		1.5		-1.5	3	

Then the same user input as listed in Table 14 was inserted in the position file as seen in Figure 47 and the automated tolerance chart for position row was generated as evident from Figure 48.

Insert the information here													
Part #	Stack Contributor	Press Fit?	Internal or External Part?	Direction of Travel	Dimension		Position tolerance details			Datum modifier details			
					Nominal	Tolerance	Tolerance Type	Tolerance Value	Tolerance Modifier	Datum modifier	Dimension		
											Nominal Dimension	Tolerance Value	Geometrical Tolerance Value
				+				3					

Figure 47: Screenshot of position pseudo test (Position row) user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
		+	1.5	-	-1.5	3	Position
		+	0	-	0	0	Bonus
		+	0	-	0	0	Shift
Total			1.5		-1.5	3	
Final Result					0	±	1.5

Figure 48: Screenshot of position pseudo test (Position row) automated tolerance chart

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the expected 1-D chart results. Hence, verifying the logic of the program.

8.4 Pseudo test case #2 and results (Bonus row)

The bonus row has two rules but nine different combinations of user inputs hence 9 different combinations were tested. If the user entered the information from Table 16 then the 1D tolerance chart shown in Table 17 was expected.

Table 16: Position pseudo test (Bonus Row) user inputs

User Inputs											
Sl. No.	Press Fit?	Internal/ External Part	Direction of Travel	Dimension		Tolerance details		Datum modifier details			
				ND	TV	GTV	Modifier	Modifier	ND	TV	GTV
1	Yes			5	2	2					
2	No	Internal	+	5	2	2	MMC				
3	No	Internal	-	5	2	2	MMC				
4	No	External	+	5	2	2	MMC				
5	No	External	-	5	2	2	MMC				
6	No	Internal	+	5	2	2	LMC				

7	No	Internal	-	5	2	2	LMC				
8	No	External	+	5	2	2	LMC				
9	No	External	-	5	2	2	LMC				

Table 17: Position pseudo test (Bonus row) expected 1-D tolerance chart

Expected 1-D Tolerance Chart						
Sl. No.	**Sign**	**Maximum**	**Sign**	**Minimum**	**Δ**	**Comment**
1	+	4	-	-4	8	Bonus
2	+	4	-	0	4	Bonus
3	+	0	-	-4	4	Bonus
4	+	0	-	-4	4	Bonus
5	+	4	-	0	4	Bonus
6	+	0	-	-4	4	Bonus
7	+	4	-	0	4	Bonus
8	+	4	-	0	4	Bonus
9	+	0	-	-4	4	Bonus
Total		20		-20	40	

Then the same user input as listed in Table 16 was inserted in the position file as seen in Figure 49 and the automated tolerance chart was generated as evident from Figure 50. The bonus row is highlighted in blue in Figure 50.

Insert the information here													
Part #	Stack Contributor	Press Fit?	Internal or External Part?	Direction of Travel	Dimension		Position tolerance details			Datum modifier details			
										Datum modifier	Dimension		
					Nominal	Tolerance	Tolerance Type	Tolerance Value	Tolerance Modifier		Nominal Dimension	Tolerance Value	Geometrical Tolerance Value
		Yes		+	5	2		2					
		No	Internal	+	5	2		2	MMC				
		No	Internal	-	5	2		2	MMC				
		No	External	+	5	2		2	MMC				
		No	External	-	5	2		2	MMC				
		No	Internal	+	5	2		2	LMC				
		No	Internal	-	5	2		2	LMC				
		No	External	+	5	2		2	LMC				
		No	External	-	5	2		2	LMC				

Figure 49: Screenshot of position pseudo test (Bonus row) user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
		+	1	-	-1	2	Position
		+	4	-	-4	8	Bonus
		+	0	-	0	0	Shift
		+	1	-	-1	2	Position
		+	4	-	0	4	Bonus
		+	0	-	0	0	Shift
		+	1	-	-1	2	Position
		+	0	-	-4	4	Bonus
		+	0	-	0	0	Shift
		+	1	-	-1	2	Position
		+	0	-	-4	4	Bonus
		+	0	-	0	0	Shift
		+	1	-	-1	2	Position
		+	4	-	0	4	Bonus
		+	0	-	0	0	Shift
		+	1	-	-1	2	Position
		+	0	-	-4	4	Bonus
		+	0	-	0	0	Shift
		+	1	-	-1	2	Position
		+	4	-	0	4	Bonus
		+	0	-	0	0	Shift
		+	1	-	-1	2	Position
		+	4	-	0	4	Bonus
		+	0	-	0	0	Shift
		+	1	-	-1	2	Position
		+	0	-	-4	4	Bonus
		+	0	-	0	0	Shift
							Position
							Bonus
							Shift
							Position
							Bonus
							Shift
Total			29		-29	58	
Final Result					0	±	29

Figure 50: Screenshot of position pseudo test (Bonus row) automated tolerance chart

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the expected 1-D chart results. Hence, verifying the logic of the program.

8.5 Pseudo test case #3 (Shift row)

The shift row has two rules but 12 different possible combinations of user inputs hence 12 different combinations were tested. If the user entered the information from Table 18 then the 1D tolerance chart shown in Table 19 was expected.

Table 18: Position pseudo test (Shift row) user inputs

User Inputs											
Sl. No.	**Press Fit?**	**Internal/ External Part**	**Direction of Travel**	**Dimension**		**Tolerance details**		**Datum modifier details**			
				ND	**TV**	**GTV**	**Modifier**	**Modifier**	**ND**	**TV**	**GTV**
1	Yes	Internal	+					MMC	5	2	2
2	Yes	External	+					MMC	5	2	2
3	Yes	Internal	+					LMC	5	2	2
4	Yes	External	+					LMC	5	2	2
5	No	Internal	+					MMC	5	2	2
6	No	Internal	-					MMC	5	2	2
7	No	External	+					MMC	5	2	2
8	No	External	-					MMC	5	2	2
9	No	Internal	+					LMC	5	2	2
10	No	Internal	-					LMC	5	2	2
11	No	External	+					LMC	5	2	2
12	No	External	-					LMC	5	2	2

Table 19: Position pseudo test (Shift row) expected 1-D tolerance chart

Expected 1-D Tolerance Chart						
Sl. No.	**Sign**	**Maximum**	**Sign**	**Minimum**	**Δ**	**Comment**
1	+	6	-	-6		Shift

2	+	6	-	-6		Shift
3	+	2	-	-2		Shift
4	+	2	-	-2		Shift
5	+	6	-	-2		Shift
6	+	2	-	-6		Shift
7	+	2	-	-6		Shift
8	+	6	-	-2		Shift
9	+	2	-	-6		Shift
10	+	6	-	-2		Shift
11	+	6	-	-2		Shift
12	+	2	-	-6		Shift
Total		46		-42		

Then the same user input as listed in Table 18 was inserted in the position file as seen in Figure 51 and the automated tolerance chart was generated as evident from Figure 52. The shift row is highlighted in blue in Figure 52.

Insert the information here													
Part #	Stack Contributor	Press Fit?	Internal or External Part?	Direction of Travel	Dimension		Position tolerance details			Datum modifier details			
										Datum modifier	Dimension		
					Nominal	Tolerance	Tolerance Type	Tolerance Value	Tolerance Modifier		Nominal Dimension	Tolerance Value	Geometrical Tolerance Value
		Yes	Internal	+						MMC	5	2	2
		Yes	External	+						MMC	5	2	2
		Yes	Internal	+						LMC	5	2	2
		Yes	External	+						LMC	5	2	2
		No	Internal	+						MMC	5	2	2
		No	Internal	-						MMC	5	2	2
		No	External	+						MMC	5	2	2
		No	External	-						MMC	5	2	2
		No	Internal	+						LMC	5	2	2
		No	Internal	-						LMC	5	2	2
		No	External	+						LMC	5	2	2
		No	External	-						LMC	5	2	2

Figure 51: Screenshot of position pseduo test (Shift row) user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	6	-	-6	12	Shift
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	6	-	-6	12	Shift
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	2	-	-2	4	Shift
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	2	-	-2	4	Shift
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	6	-	-2	8	Shift
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	2	-	-6	8	Shift
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	2	-	-6	8	Shift
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	6	-	-2	8	Shift
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	2	-	-6	8	Shift
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	6	-	-2	8	Shift
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	6	-	-2	8	Shift
		+	0	-	0	0	Position
		+	0	-	0	0	Bonus
		+	2	-	-6	8	Shift
Total			46		-42	88	
Final Result					2	±	44

Figure 52: Screenshot of position pseudo test (Shift row) automated tolerance chart

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the expected 1-D chart results for all the three-pseudo test cases. Hence, verifying the logic of the program.

8.6 Test case #1 (Position row)

Three test cases were performed on position file to validate all the three rows. For position row, test case can be found in [Krulikowski, p 10-5].

As evident from [Krulikowski, p 10-5], the position test case #1 like the runout and profile test consists of certain size dimensions. Hence, the same procedure of adding a size and basic dimension sheet and final result sheet was done to successfully execute this test as shown in Figure 53.

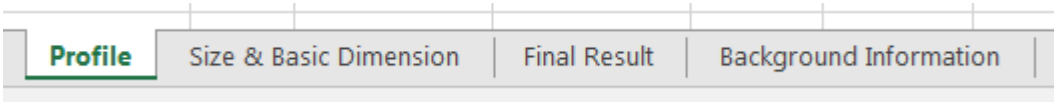


Figure 53: Screenshot of position and size & basic dimension combined files

Based on the stack path, the information was entered as shown in Figure 54 and the automated chart was generated as shown in Figure 55 for size and basic dimensions.

Insert the information here					
Part #	Stack Contributor	Tolerance Type	Direction of Travel	Nominal Dimension	Tolerance Value
	P-27	Size Dimension	-	2.1	0.1
	P-27	Basic Dimension	+	40	
	P-27	Size Dimension	-	2.1	0.1

Figure 54: Screenshot of size & basic dimension test #1 user inputs

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
	P-27	-	-2	-	-2.2	0.2
	P-27	+	40	+	40	0
	P-27	-	-2	-	-2.2	0.2
Total			36		35.6	0.4

Figure 55: Screenshot of size & basic dimension test #1 automated tolerance chart

Then the information was entered as shown in Figure 56 and the automated chart was generated as shown in Figure 57 for position tolerance.

Insert the information here													
Part #	Stack Contributor	Press Fit?	Internal or External Part?	Direction of Travel	Dimension		Position tolerance details			Datum modifier details			
										Datum modifier	Dimension		
					Nominal	Tolerance	Tolerance Type	Tolerance Value	Tolerance Modifier		Nominal Dimension	Tolerance Value	Geometrical Tolerance Value
P-27		No	Internal	+	40	0	Position	0.1					
P-27		No	Internal	-	2.1	0.1	Position	0.1					

Figure 56: Screenshot of position test #1 user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
P-27		+	0.05	-	-0.05	0.1	Position
		+	0	-	0	0	Bonus
		+	0	-	0	0	Shift
P-27		+	0.05	-	-0.05	0.1	Position
		+	0	-	0	0	Bonus
		+	0	-	0	0	Shift
Total			0.1		-0.1	0.2	

Figure 57: Screenshot of position test #1 automated tolerance chart

Final Result		
Total Maximum	Total Minimum	Δ
36.1	35.5	0.6
OR		
35.8	±	0.3

Figure 58: Screenshot of test #1 final result

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the manual results. Thus, verifying the position row.

8.7 Test case #2 (Bonus row)

For bonus row, test case can be found in [Krulikowski, p 11-9]. Based on the stack path, the information was entered as shown in Figure 59 and the automated chart was generated as shown in Figure 60 for size dimension.

Insert the information here					
Part #	**Stack Contributor**	**Tolerance Type**	**Direction of Travel**	**Nominal Dimension**	**Tolerance Value**
X-128	F	Size Dimension	+	8.25	0.25
X-128	A	Size Dimension	-	7	0.1

Figure 59: Screenshot of size and basic dimension test #2 user inputs

Automated Tolerance Chart						
Part #	**Stack Contributor**	**Sign**	**Maximum (max/min)**	**Sign**	**Minimum (max/min)**	**Δ**
X-128	F	+	8.5	+	8	0.5
X-128	A	-	-6.9	-	-7.1	0.2
Total			1.6		0.9	0.7

Figure 60: Screenshot of size and basic dimension test #2 automated tolerance chart

Then, the information was entered for position file as shown in Figure 61 and the automated chart was generated as shown in Figure 62.

Insert the information here													
Part #	**Stack Contributor**	**Press Fit?**	**Internal or External Part?**	**Direction of Travel**	**Dimension**		**Position tolerance details**			**Datum modifier details**			
										Datum modifier	**Dimension**		
					Nominal	**Tolerance**	**Tolerance Type**	**Tolerance Value**	**Tolerance Modifier**		**Nominal Dimension**	**Tolerance Value**	**Geometrical Tolerance Value**
X-128	F	No	External	+	8.25	0.25	Position	0.5	LMC				

Figure 61: Screenshot of position test #2 user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
X-128	F	+	0.25	-	-0.25	0.5	Position
		+	0.5	-	0	0.5	Bonus
		+	0	-	0	0	Shift
Total			0.75		-0.25	1	

Figure 62: Screenshot of position test #2 automated tolerance chart

Final Result		
Total Maximum	Total Minimum	Δ
2.35	0.65	1.7
OR		
1.5	±	0.85

Figure 63: Screenshot of test #2 final result

The total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the manual results. Thus, verifying the bonus row of position file.

8.8 Test case #3 (Shift row)

For shift row, test case can be in [Krulikowski, p 12-7]. Based on the stack path, the information was entered as shown in Figure 64 and the automated chart was generated as shown in Figure 65 for size and basic dimension.

Insert the information here					
Part #	Stack Contributor	Tolerance Type	Direction of Travel	Nominal Dimension	Tolerance Value
	B	Basic Dimension	+	20	0
	F	Size Dimension	-	4.2	0.1
	A	Size Dimension	-	8.125	0.125

Figure 64: Screenshot of size and basic dimension test #3 user inputs

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
	B	+	20	+	20	0
	F	-	-4.1	-	-4.3	0.2
	A	-	-8	-	-8.25	0.25
Total			7.9		7.45	0.45

Figure 65: Screenshot of size and basic dimension test #3 automated tolerance chart

Then, the information for position was entered as shown in Figure 66 and the automated chart was generated as shown in Figure 67.

Insert the information here													
Part #	Stack Contributor	Press Fit?	Internal or External Part?	Direction of Travel	Dimension		Position tolerance details			Datum modifier details			
					Nominal	Tolerance	Tolerance Type	Tolerance Value	Tolerance Modifier	Datum modifier	Dimension: Nominal Dimension	Dimension: Tolerance Value	Geometrical Tolerance Value
	F	No	Internal	-	4.2	0.1	Position	0.16	MMC	MMC	8.125	0.125	0.15

Figure 66: Screenshot of position test #3 user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
	F	+	0.08	-	-0.08	0.16	Position
		+	0	-	-0.2	0.2	Bonus
		+	0.15	-	-0.4	0.55	Shift
Total			0.23		-0.68	0.91	

Figure 67: Screenshot of position test #3 automated tolerance chart

Final Result		
Total Maximum	**Total Minimum**	**Δ**
8.13	6.77	1.36
OR		
7.45	±	0.68

Figure 68: Screenshot of test #3 final result

For all the three test cases, the total of maximum, minimum and Δ column of the automated tolerance chart matched 100% to the manual 1-D chart results. Thus, verifying the position file.

8.9 File limitations

With nine different user inputs combinations for bonus row and twelve different combinations for shift row been taken care of, the position file does not have any known limitation.

CHAPTER 9: Development of the Master File

9.1 Combination of individual files

Once the six individual files were tested, various ways were considered to merge all the individual files into one master file. The most difficult part of combining the files into one file were the different number and type of user inputs. Attempt was made to bring all the files into a single file. This increased the number of user inputs and made the simple format very complex to look at. Hence, it was decided to proceed further with the method adopted for runout, profile and position test cases where size and dimension file was inserted as a sheet and a separate Final Result sheet was made to display the end results. Figure 69 below shows the different tabs and their placements. The tabs have been arranged alphabetically. The final result sheet comprises of the sum of the maximum column from each sheet, sum of the minimum column from each sheet and sum of the tolerance column from each sheet as shown in Figure 70. No new limitation was recognized as the master file is basically a combination of the individual files.

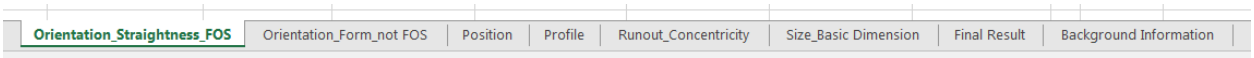


Figure 69: Screenshot of the tabs in the master file

Final Result		
Total Maximum	**Total Minimum**	**Δ**
0	0	0
OR		
0	±	0

Figure 70: Screenshot of final result sheet format

9.2 User test

After the files were combined into one file, Kristen Hahyeon Kim, undergraduate research assistant at DDML was asked to use it to conduct few examples from *Tolerance Stacks Using G.D.&T.* [4]. She just began to study GD&T a week before using 1-D Tolerance Chart Automate and has never conducted tolerance analysis. Hence, she was an ideal user for this tool as this project's main aim is to free the user from mastering the rules. The following is some valuable feedback she provided:

- Instead of writing the name of the GD&T geometric characteristics like position, profile or runout, it would be useful to have symbols as someone who hasn't used GD&T at all or for a while would be confused with the names
- Some terminology known to GD&T experts such as "To stack" or "Thru stack" or "External part" must be explained by adding a comment near those entry tabs.
- In some tabs like position, size dimensions are entered to calculate the virtual condition but not processed in the 1D automated chart. It is assumed that if size dimension is entered once in any tab than it shall be processed automatically and need not be entered again in the size and basic dimension tab. It was suggested that a user manual of 1-2 pages be created to help the user get started with using this tool.
- While navigating through the cells in Excel file, she accidentally deleted the formulae and advised to lock down the cells containing formula.

9.3 Feedback incorporation after user review

After the user test, the symbols font SWGDT was downloaded from the web and included in the Microsoft directory to incorporate the symbols instead of naming the geometric characteristics as seen from Figure 71 which shows the tolerance type column for orientation,

straightness and cylindricity (FOS) sheet. However, due to the restrictions in MS Excel for drop down menus, the symbol is not visible (Figure 72), as special font type capability is not available for drop down menu. As seen in Figure 72, instead of the symbols, keyboard shortcuts of the symbol is displayed. This problem is been looked into and is resolvable.

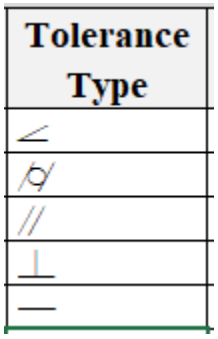


Figure 71: Symbols in tolerance type column from orientation, straightness and cylindricity (FOS) file

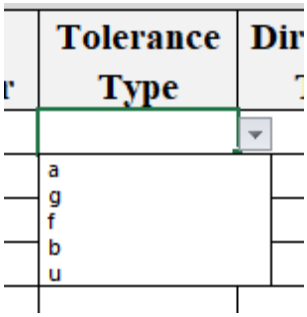


Figure 72: Screenshot of drop down menu showing keybard shortcuts of the symbols instead of the symbols

Following terminologies seemed confusing to the user. Hence, comments have been added in those columns explaining the term as seen in Figure 73.

- Internal part: Parts that are hollow like holes, gaps or clearance between mating parts.
- External part: Solid parts like solid shaft, block
- To stack: The stack ends or starts in that part
- Thru stack: The stack passes through the part
- Adjacent to mating: The two mating parts are touching each other at that point
- Offset to mating: The two parts are not touching at that point

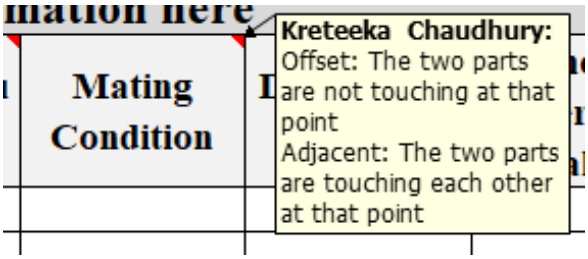


Figure 73: Screenshot of comments incorporated in the file

As per user input, a user manual has been created to provide an overview of how to use and navigate through the tool. The user manual can be found in Appendix B. Also, all the formulae cells have been locked and protected so that the user does not change or delete any formula from the file by mistake.

9.4 Surrogate gearbox test case

The surrogate gear box assembly was tested using 1-D Tolerance Chart Automate by Kaushalya Putta, Undergraduate Research Assistant in DDML. The test case can be found in [Krulikowski, p 19-8]. Based on the stack path the size and basic dimension, position, runout and profile specifications were entered in their respective sheet as evident from Figure 74-82.

Insert the information here					
Part #	**Stack Contributor**	**Tolerance Type**	**Direction of Travel**	**Nominal Dimension**	**Tolerance Value**
X115		Size Dimension	-	51	0.04
X115		Size Dimension	-	13.5175	0.0125
X104		Size Dimension	+	13.4875	0.0125
X100		Basic Dimension	-	68.8	
X100		Basic Dimension	+	135.3	
X124		Size Dimension	-	14.12	0.05

Figure 74: Screenshot of size and basic dimension sheet master file test user inputs

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
X115		-	-50.96	-	-51.04	0.08
X115		-	-13.505	-	-13.53	0.025
X104		+	13.5	+	13.475	0.025
X100		-	-68.8	-	-68.8	0
X100		+	135.3	+	135.3	0
X124		-	-14.07	-	-14.17	0.1

Figure 75: Screenshot of size and basic dimension sheet master file test automated tolerance chart

Insert the information here													
Part #	Stack Contributor	Press Fit?	Internal or External Part?	Direction of Travel	Dimension		Position tolerance details			Datum modifier details			
					Nominal	Tolerance	Tolerance Type	Tolerance Value	Tolerance Modifier	Datum modifier	Dimension: Nominal Dimension	Dimension: Tolerance Value	Geometrical Tolerance Value
1	X100	Yes	Internal	+	30.83	0.03	⌖	0.4	MMC				

Figure 76: Screenshot of position sheet master file test user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
1	X100	+	0.2	-	-0.2	0.4	Position
		+	0.06	-	-0.06	0.12	Bonus
		+	0	-	0	0	Shift

Figure 77: Screenshot of position sheet master file test automated tolerance chart

Insert the information here								
Part #	Stack Contributor	Tolerance Type	Any Datum?	Direction of Travel	Dimension			Geometrical Tolerance Value
					Nominal	(+) Tolerance Value	(-) Tolerance Value	
X100		⌓	Yes	+	135.3			0.2

Figure 78: Screenshot of profile sheet master file test user inputs

Automated Tolerance Chart							
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ	Comment
		+	0.1	-	-0.1	0.2	

Figure 79: Screenshot of profile sheet master file test automated tolerance chart

Insert the information here			
Part #	Stack Contributor	Tolerance Type	Geometrical Tolerance Value
X115		↗	0.2
X104		↗	0.1

Figure 80: Screenshot of runout sheet master file test user inputs

Automated Tolerance Chart						
Part #	Stack Contributor	Sign	Maximum (max/min)	Sign	Minimum (max/min)	Δ
X115		+	0.1	-	-0.1	0.2
X104		+	0.05	-	-0.05	0.1

Figure 81: Screenshot of runout sheet master file test automated tolerance chart

Final Result		
Total Maximum	Total Minimum	Δ
1.975	0.875	1.25
OR		
1.425	±	0.625

Figure 82: Screenshot of master file test final result

The results matched 100% to the manual calculations performed previously by her. Thus, verifying the master file.

CHAPTER 10: Conclusion

10.1 Summary

The purpose of the project was to develop a tool that would perform 1-D maximum and minimum chart tolerance stack analysis automatically after the user provides the required inputs. The tool was developed with the assumption that the user is capable of finding the stack path and is aware of GD&T schemes. The main intention of this project is to make the 1D chart process more efficient, avoid repetition and mundane work.

During the process of this project, pseudocodes has been developed for every possible combinations of the user inputs and can serve as a backbone for similar developments using alternative platforms. The six individual files made can also be used standalone for parts that consists of only one type of tolerance class. In addition, the master file along with the user manual will allow anyone who is capable of finding the stack path to perform 1-D maximum and minimum chart without knowing the tolerance analysis rules.

This research has developed a tool, 1-D Tolerance Chart Automate that will perform 1-D maximum and minimum chart automatically once the user enters the required inputs. In the process, six individual files and one master file has been created. These files have been tested using various different parts. The summary of tests is listed in Table 20 below.

Table 20: Summary of tests

Category	Test Case	1D Tolerance Chart Automate Tolerance Result	Manual Result	Accuracy %
Size and basic dimension	Steps	6.50	6.50	100
Runout and concentricity	Two cylinders	0.30	0.30	100
Profile	Bolt pattern	2.20	2.20	100
Orientation and form (not FOS)	Rotor and cover	0.16	0.16	100
	Cover and housing	0.05	0.05	100
Orientation, straightness and cylindricity (FOS)	Rotor and housing	0.25	0.25	100
	Bracket and spacer	2.80	2.80	100

Position	Bolt pattern	0.60	0.60	100
	Bolt pattern	1.33	1.33	100
	Coaxial cylinders	1.70	1.70	100
Master file	Surrogate gear box	1.25	1.25	100

The test results in Table 2 prove that the files are verified, and the algorithm used is accurate. As variety of different parts would be tested using this tool, more shortcomings are expected to come forward. The tool developed currently has the following known limitations –

1. The tool cannot find the stack path and the user is responsible to determine the stack path
2. The user needs to be consistent with the data input as the tool currently is not capable of finding user input mistakes like double entries
3. Size and basic dimension sheet can be used only for bilateral geometrical dimension
4. The final result sheet is not capable of showing the entire tolerance chart
5. The tool can only be used for parts and not assemblies.

10.2 Additional Applications and Future Work

The next immediate step would be to do the following –

- Find a way to display symbols in the drop down list
- Display full 1D tolerance chart sheet in the final result sheet

As mentioned in the limitations, the tool can only be used for part level at this stage. Hence, future work involves making something similar for assemblies.

Apart from being used by DDML lab members to conduct 1-D tolerance analysis, this tool can be used by small or mid-size companies whose employees perform 1-D maximum and minimum charts manually.

It can be also be used by Professors who teach GD&T courses. This will allow the students to have access to a smart tool before they step into the industry.

In addition, with the advancement of artificial intelligence, it would be interesting to see if software can be developed using the pseudocodes developed for this research project. This software will be capable of reading a scanned pdf file or drawing and will be able to perform 1D minimum and maximum chart automatically once the area of interest is indicated by the user.

REFERENCES

[1] Anon, (2018). [online] Available at: http://www.cqeacademy.com/cqe-body-ofknowledge/product-process-design/technical-drawings-gdt/ [Accessed 8 Sept. 2017].

[2] Shah, Jami J. “Part 2: Tolerance Analysis Methods”. Geometric Dimensioning & Tolerancing (GD&T): Introduction Short Course. June 2017. pp. 5, 16, 34

[3] Software, S. (2018). *PLM Visualization: Siemens PLM Software*. [online] Plm.automation.siemens.com. Available at: https://www.plm.automation.siemens.com/en/products/teamcenter/plm-platformcapabilities/visualization/index.shtml [Accessed 12 Oct. 2017].

[4] Alex Krulikowski. *Tolerance Stacks using G.D.&T.* Effective Training Inc., 1994*.

[5] Shah, Jami J. “1D charts: Cheat Sheet”. Geometric Dimensioning & Tolerancing (GD&T): Introduction Short Course. June 2017. pp. 1

**Permission requested*

APPENDIX A: Abbreviation List

- TT = Tolerance type
- DT = Direction of travel
- ND = Nominal dimension
- TV = Tolerance value
- LSC = Left sign column
- MAXC = Maximum column
- RSC = Right sign column
- MINC = Minimum column
- +TV = (+) Tolerance value
- -TV = (-) Tolerance value
- GTV = Geometrical tolerance value
- MC = Mating condition
- MMC = Maximum material condition
- LMC = Least material condition
- VC = Virtual condition
- FOS = Feature of size

APPENDIX B: User Manual

1D Tolerance Chart Automate consists of six different sheets which includes all the thirteen geometric characteristics and dimensions:

1. Size and basic dimension
2. Runout and concentricity
3. Profile
4. Orientation and form (not FOS)
5. Orientation, straightness and cylindricity (FOS)
6. Position

Things to consider –

- For size and basic dimension to be accounted for in the final result, it must be entered in the size and basic dimension sheet even though it has been entered in other sheets like position. The size and basic dimensions entered in the position sheet is required to calculate the bonus and shift tolerances or VC, MMC and LMC when entered in the orientation and form sheets.
- The drop down menu is currently not capable of showing the symbols. It is rather showing the keyboard shortcuts to the symbols. Table 21 consists of the list of keyboard shortcuts associated with the symbols.
- GD&T terminologies like to stack, adjacent mating and external part have been explained by using comment feature in the file.
- File limitation –
    - Only performs 1D chart at part level
    - Currently assumes bilateral size tolerance

Table 21: GD&T symbols and its keyboard shortcuts

Type of Tolerance	Geometric Characteristics	Symbol	Shortcut
Form	Straightness		u
	Flatness		c
	Circularity		e
	Cylindricity		g
Profile	Profile of a line		k
	Profile of a surface		d
Orientation	Angularity		a
	Perpendicularity		b
	Parallelism		f
Location	Position		j
	Concentricity		r
	Symmetry		i
Runout	Circular Runout		h
	Total Runout		t
Dimension			o
Maximum material condition			m